# ADVANCED ENGINEERING MATERIALS

Advanced Measurement in
Wear and Friction Testing Webinar


NPL National Physical Laboratory

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NPL
National Physical Laboratory

# Advanced Measurement in Wear and Friction Testing

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Advanced Engineering Materials
National Physical Laboratory

Advanced Engineering Materials Webinar, July 13th 2021

# Summary of Talk

- Why do we need to measure Wear and Friction (Tribology)?
- Development of documentary standards
- Surface characterisation
- Recent measurement methods
- Next steps

# Wear and Friction

*Wear is removal of material from contacting surfaces in relative motion*

*Friction is force generated by contacting surfaces that resists relative motion*

- Complex phenomena dependent on a many different parameters
- There are many different types of wear depending on types of interaction
- Wear is major and ubiquitous source of losses to commerce and society
  - Most industrial sectors – transport, mineral extraction, manufacturing
- Friction needs to be controlled
  - Often reduced for energy efficiency but not always
- Impacts on sustainability, efficient energy generation and use, competitiveness of industry

# Examples where Wear and Friction are Important

Wind turbines

Cam shaft

Hard drive


Manufacturing (Sprite can)

Digger teeth, mineral extraction

Joint prothesis

Shoe sole

Bicycle

Brake

# Different Types of Wear

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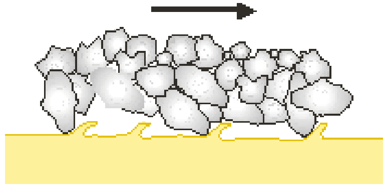
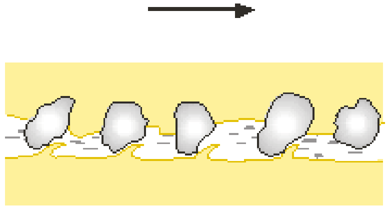
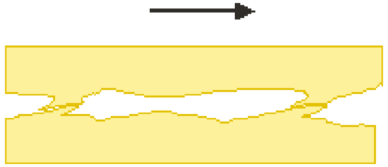
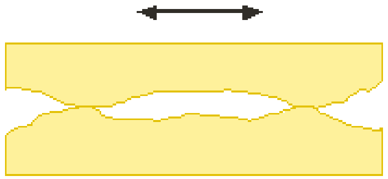

Abrasive wear from moving contact with hard sharp granular materials

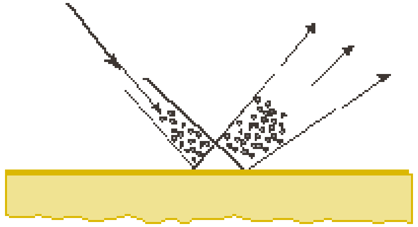
2

Abrasive wear from hard sharp particles trapped between moving surfaces

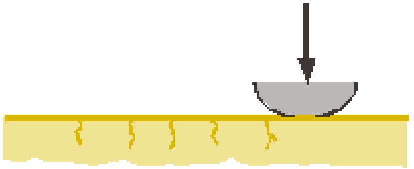
3

Adhesive wear from the rubbing together of relatively smooth surfaces

4

Fretting from small oscillatory movements between relatively smooth surfaces

5

Cavitation erosion from the collapse of vacuum vapour bubbles

6

Particle erosion from hard particles in a stream of fluid

7

The release of particles from a surface as a result of fatigue

# Wear and Friction Testing

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- Measurement task: An expert analyses the application, identifies the rate limiting interfacial interaction and then designs a repeatable laboratory experiment that reproduces the same wear mechanism and failure modes as seen in service.
- Normally needs considerable experience to carry this out

- Can I have any confidence that laboratory tests will correlate with real-world service performance?

Real world service

Laboratory test
- actual parts & geometry
- bespoke test method

Benchtop standard coupon test

- Increasing ease of instrumentation
- Increasing control
- Increasing abstraction
- Decreasing cost
- Decreasing time

- There are standard tests which are useful for initial ranking during material development. However to obtain specific ranking which correlate with real-world service performance, bespoke engineered solutions are usually required.

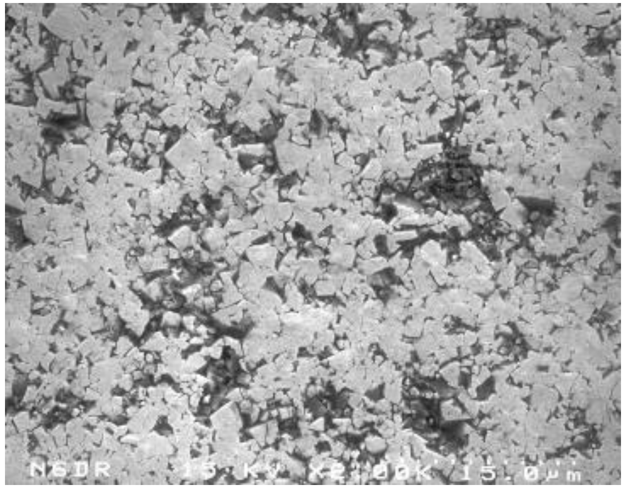
# Wear Testing Approaches

- Carry out field tests
  - Often expensive, control is not good, information obtained is poor
- Reproduce application exactly in laboratory
  - Allows more certainty that you are testing what is required
  - Can instrument thoroughly to get more information
  - Very expensive
- Carry out many, many wear tests to sample test condition space quickly
  - Not usually possible to instrument fully or examine samples that thoroughly so lower information for each test
- Carry out very carefully controlled laboratory tests which are highly instrumented to give as much information as possible
  - Provides deeper understanding of mechanisms that occur

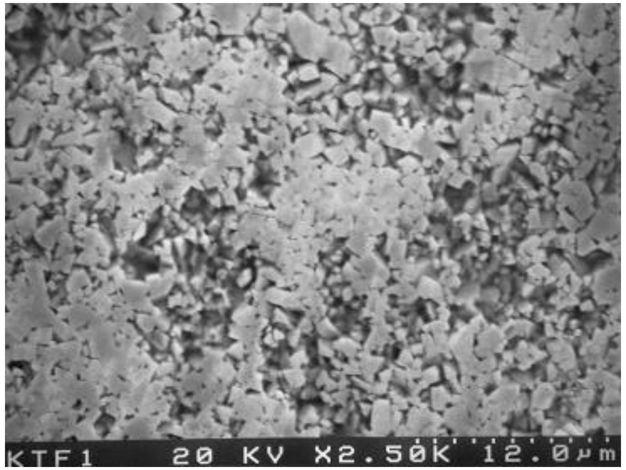
PREFERRED APPROACH

# Benefit to Industry

- Carried out survey of industry with Michael Neale mid ‘90s
  - Found wear testing could lead directly to savings of 0.25 % of turnover (equated to £650 M in 1995)
  - Improved design and improved data for design
  - Solutions to problems
- Two examples
  - Slipper blade for production of concrete roof tiles – abrasion main form of damage
    - Large programme of testing ~50 materials by NPL to see if better material was available
    - Developed modified lab test and matched mechanisms
    - End result was that original material was best
  - Hardmetal manufacturer, new composition for punches for Al can manufacture – lower density. NPL measured mechanical properties and also found tribological performance was as good. Gave saving of £6M per annum, also applied to sub-sea valves with estimated potential saving of £2M per annum.



**Actual slipper blade**




**Test sample**

# Effect of Test Variables

- Critical in developing robust test procedures
- Leads to better standards for testing
- Need to be considered in design of tests
- Parameters include:
  - Load, speed, materials, test environment, contact geometry

- Examples:
  - Abrasion of Hardmetals
  - Effect of humidity

# Abrasion of WC/Co Hardmetals

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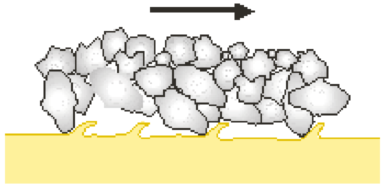
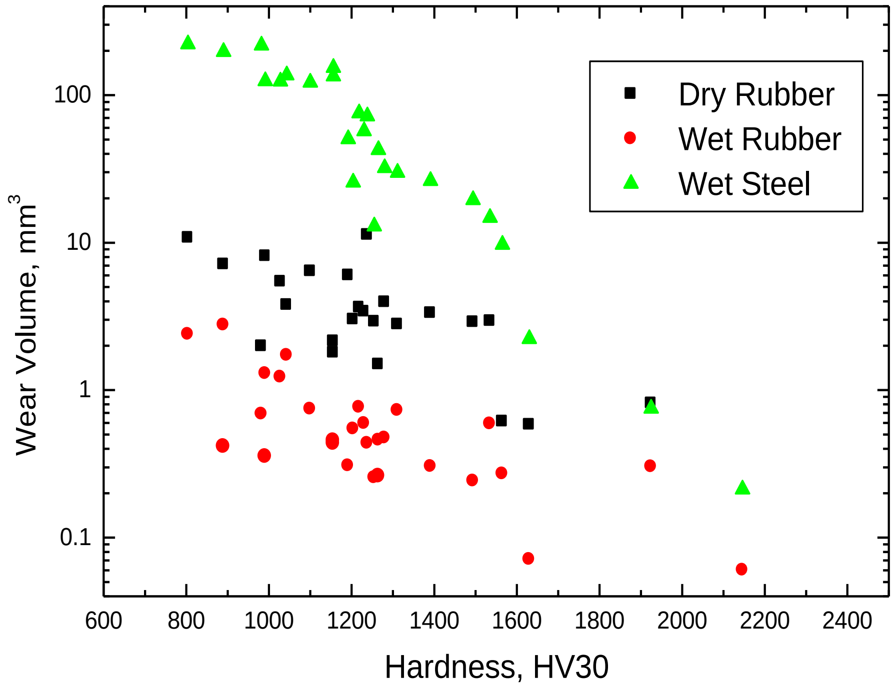
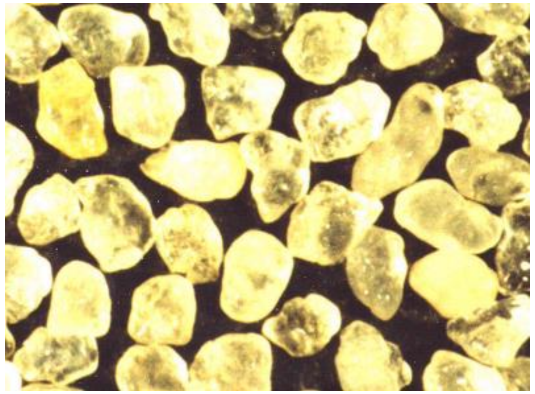
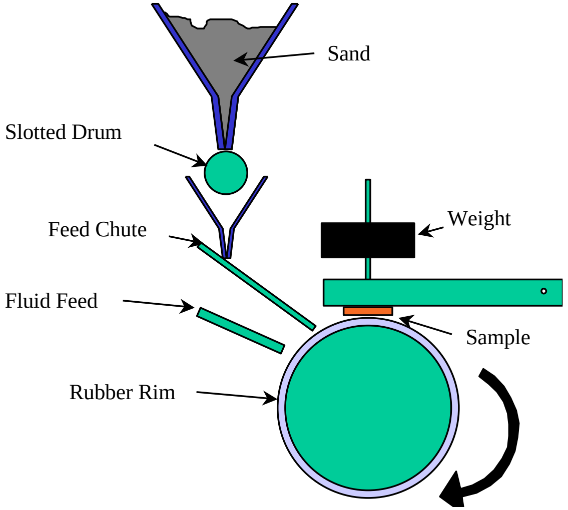
- About 70 % of wear issues in industry are due to abrasion
- Relevant to materials handling, mining, damage from contamination
- Particularly important for WC/Co hardmetal tool materials



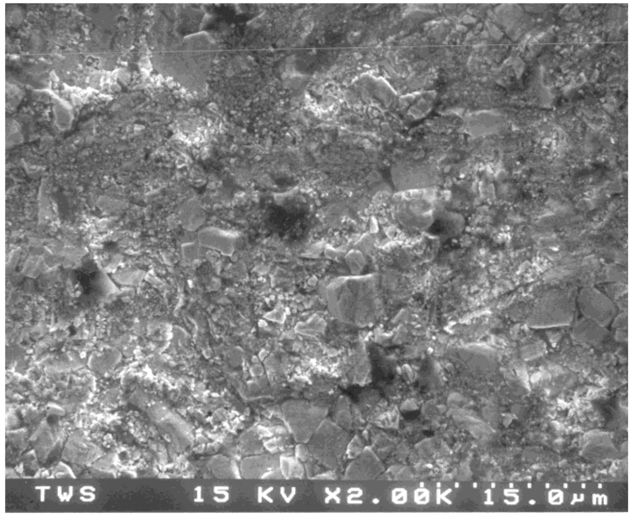


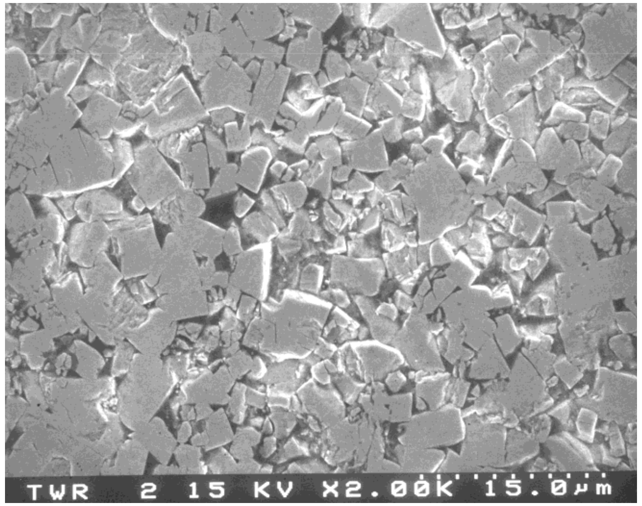
Silica sand abrasive




Schematic of test



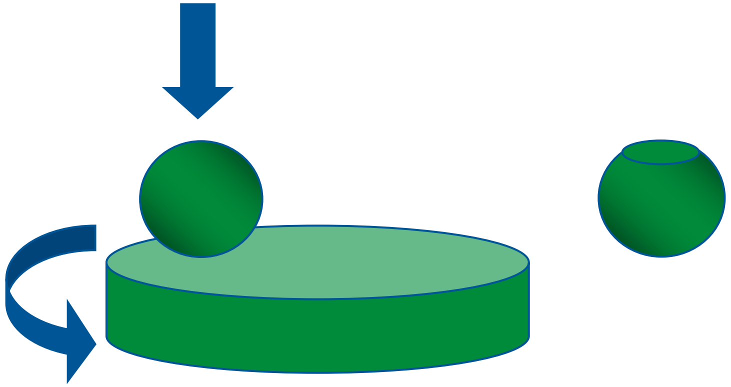

Wear surface for wet steel test conditions

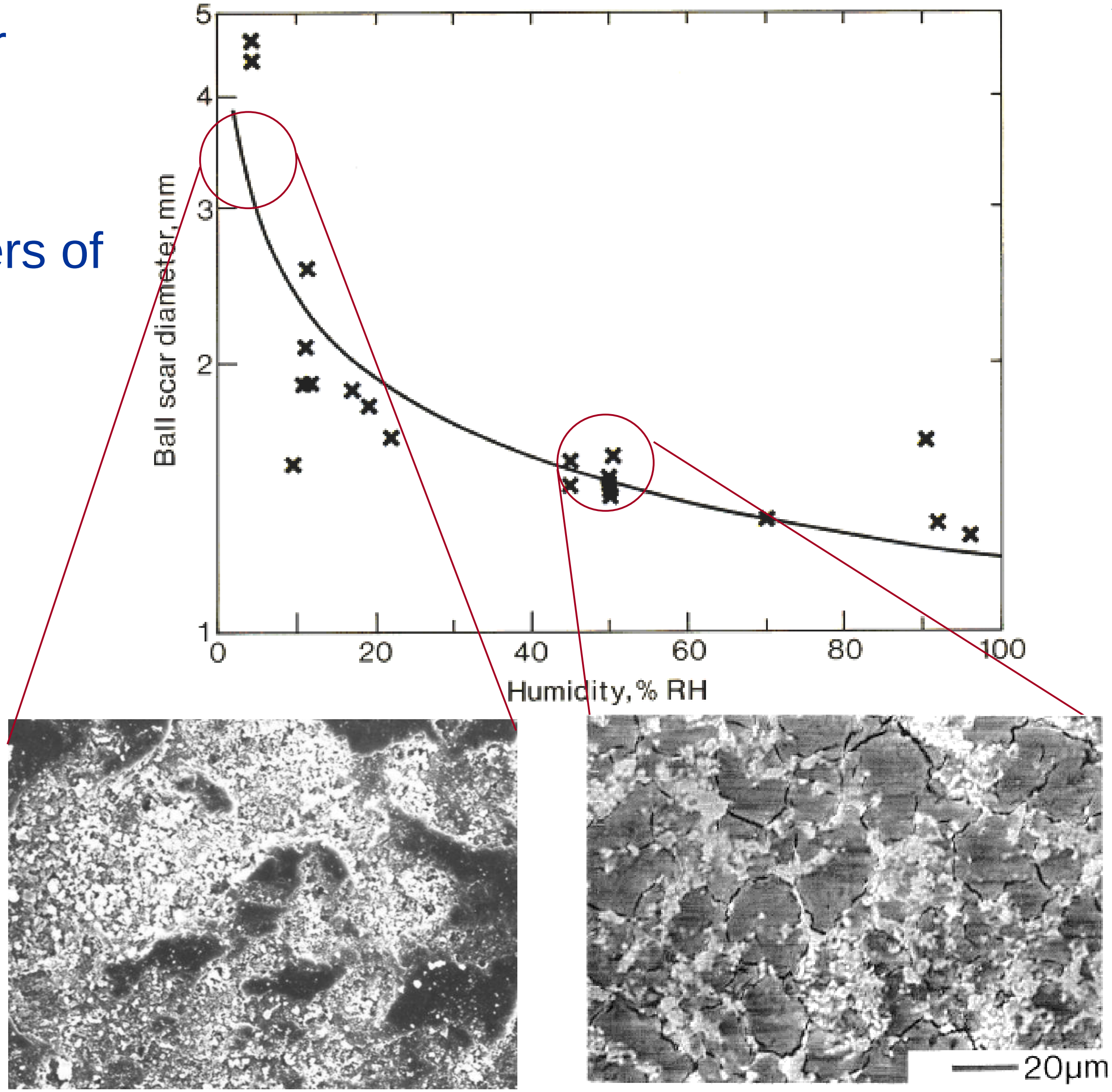



Wear surface for wet rubber test conditions

# Effect of Humidity – Reaction with Environment

- Example of alumina with water vapour in air
- Pin-on-disc
- Large effect of humidity – orders of magnitude in volume terms



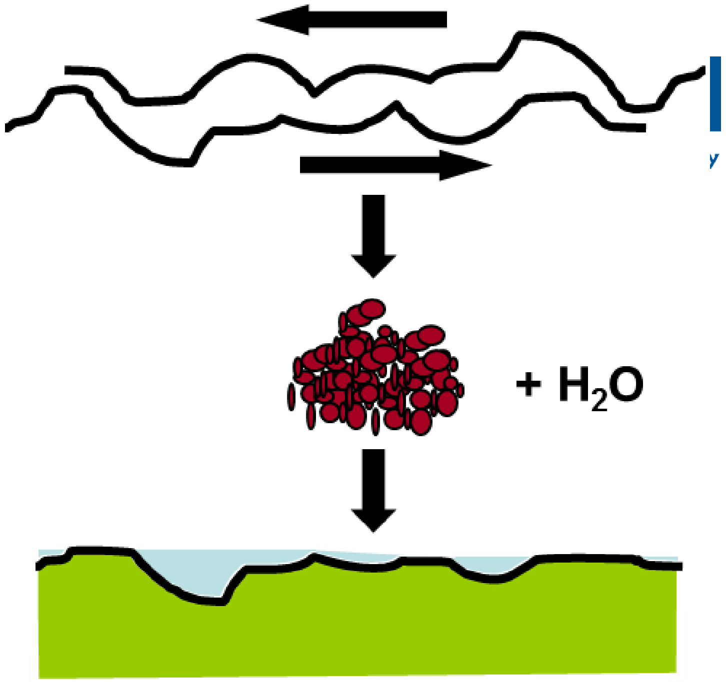


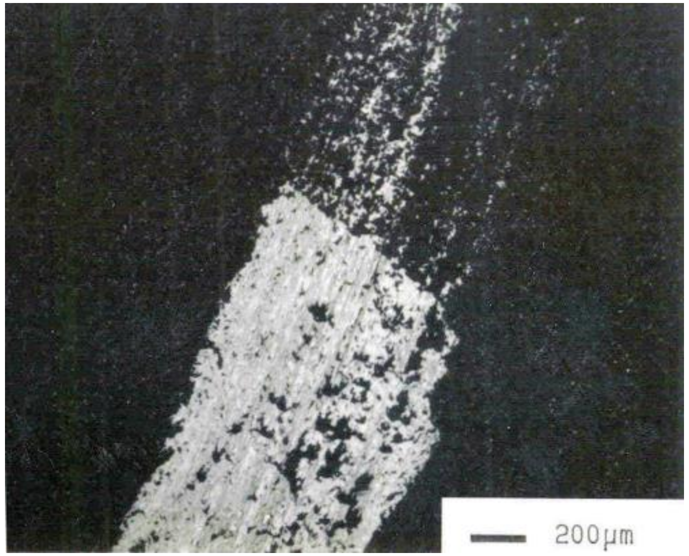

**Volume of Wear**

| | |
|---|---|
| **80 % humidity** | **0.05 $mm^3$** |
| **3 % humidity** | **4 $mm^3$** |

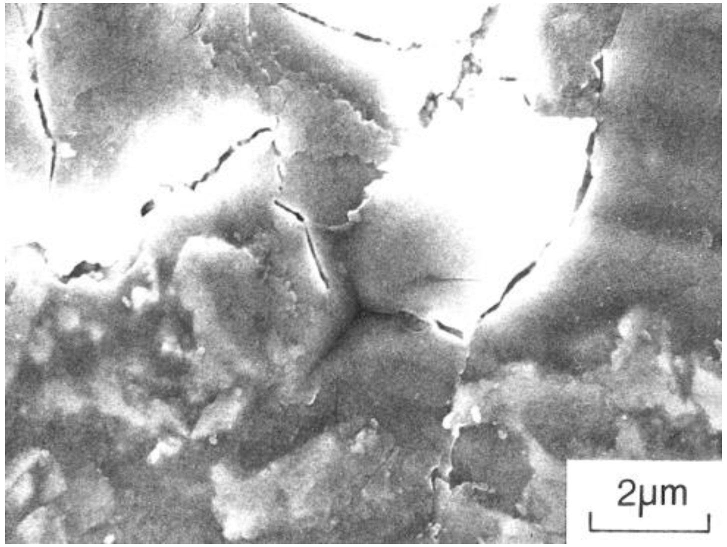
# Tribochemistry for Alumina

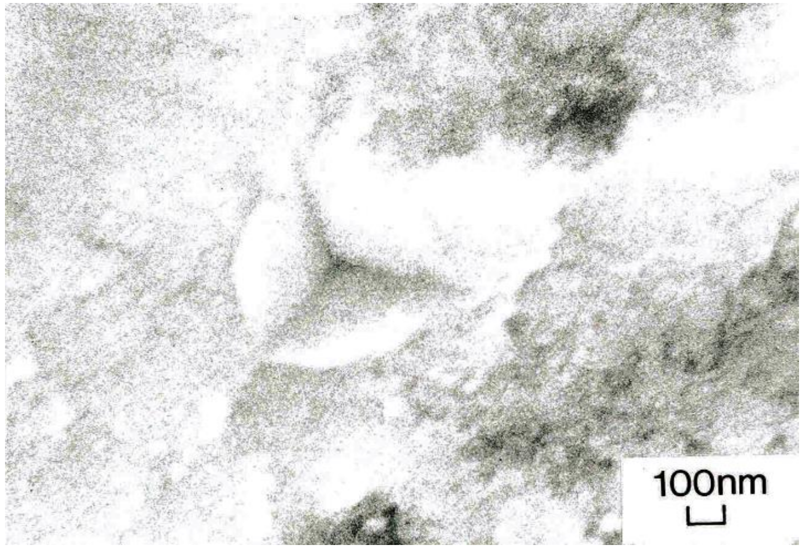
- Investigated effect with range of tools:
  - SIMS, SEM, Nanoindentation, TEM, XRD, adhesion test
- Found that fine debris (~20 nm) produced in initial contact hydrated to form soft lubritious layer on surface




Adhesive tape adhesion test showing removal of soft layer (top right)

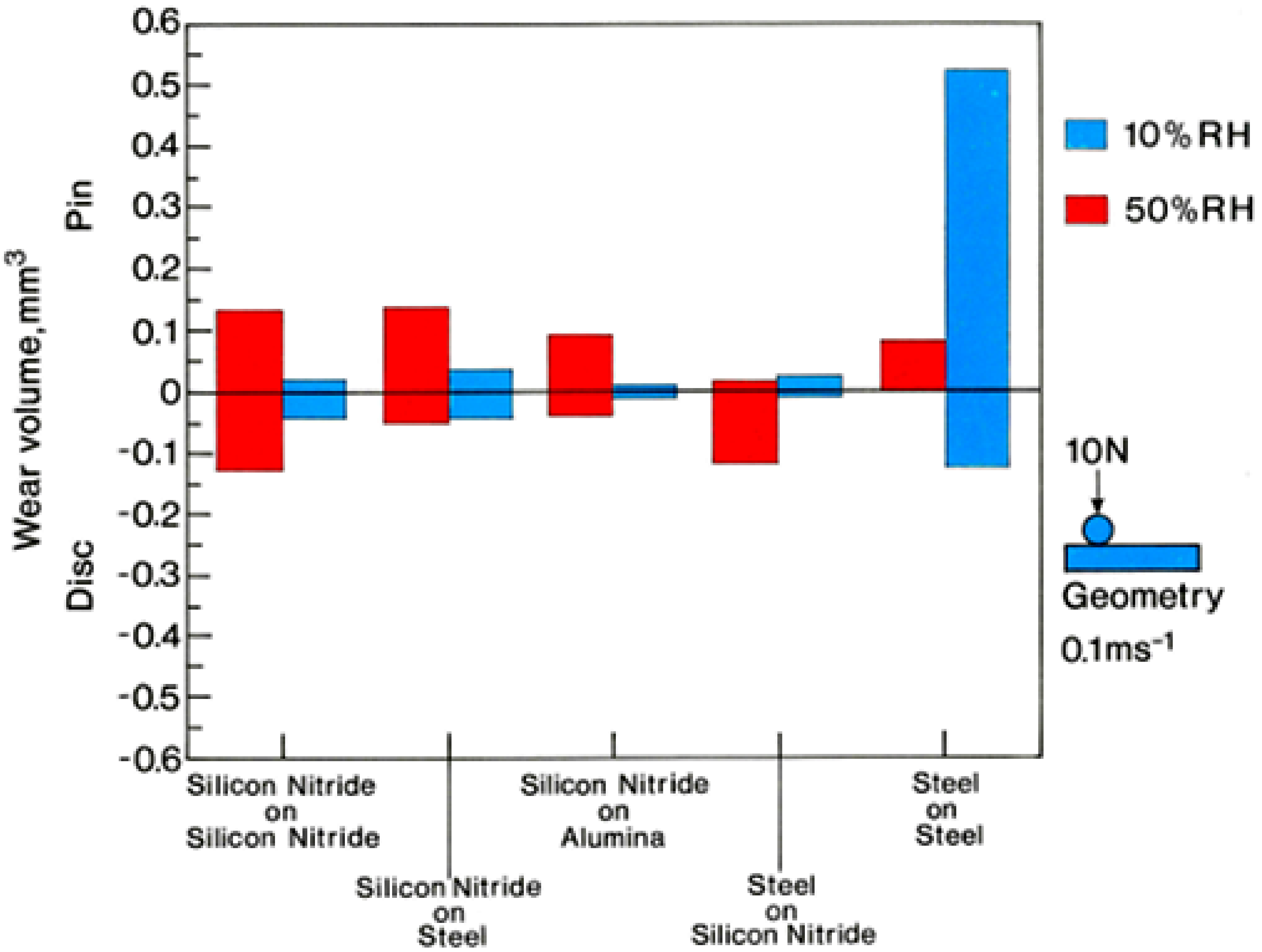



Nanoindentation into hard (left) and soft (right) regions of surface

# Effect of Humidity on Other Materials

- There is an effect from humidity on most materials
- Some examples shown here for ball on disc tests



# Documentary standards and Interlaboratory Exercises

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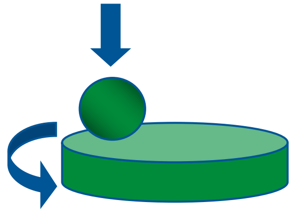
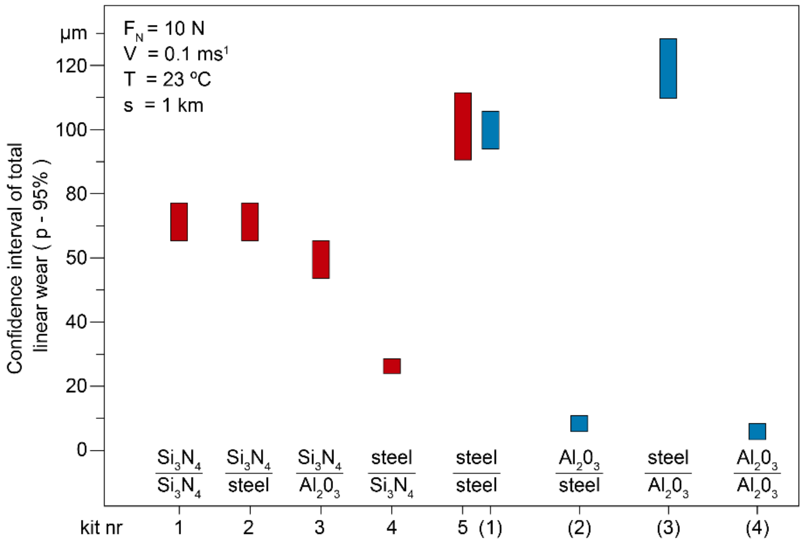
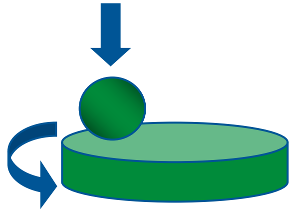
- Documentary standards are important as a basis for common agreement on results and as a basis for assured data
- An essential element of documentary standards which determines how reproducible and repeatable tests are, different laboratories carry out same test on same materials
- Historically, progress was held back through concern about poorly planned OECD IRG Engineering Materials interlaboratory exercise on copper, brass bronze and steel in 1960s
- Recognition of lack of agreed basis for testing led to interlaboratory exercises:
  - pin on disc sliding wear under VAMAS
    - 2 exercises
    - Basis for ASTM G99 and recently ISO standards
  - Reciprocating wear for ASTM
    - Basis for ASTM G133 standard
  - EU funded SMT Crater project on micro-scale abrasion
    - Basis for CEN and ISO standards
  - Recent EU funded project on micro and nanoscale scratch experiments
    - New CEN standard just published

# Interlaboratory Exercise Results

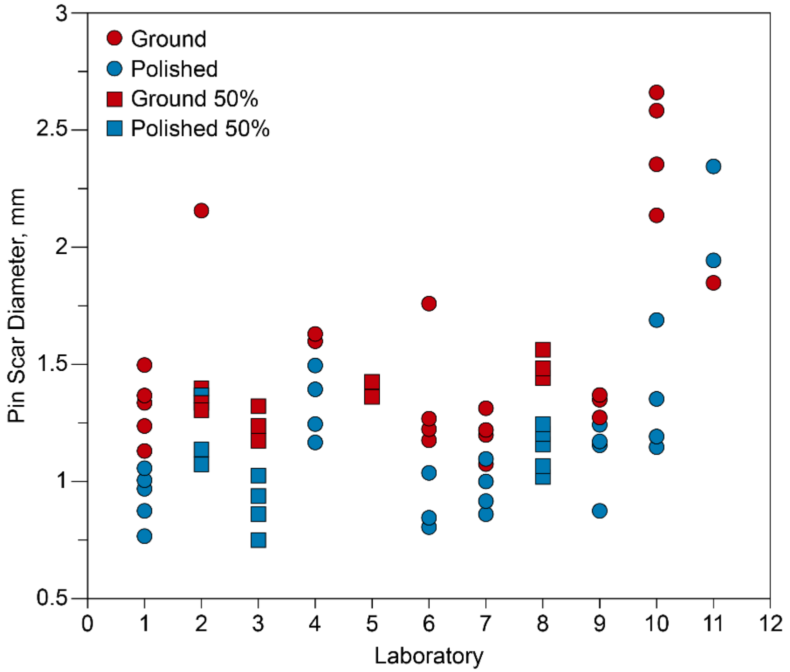


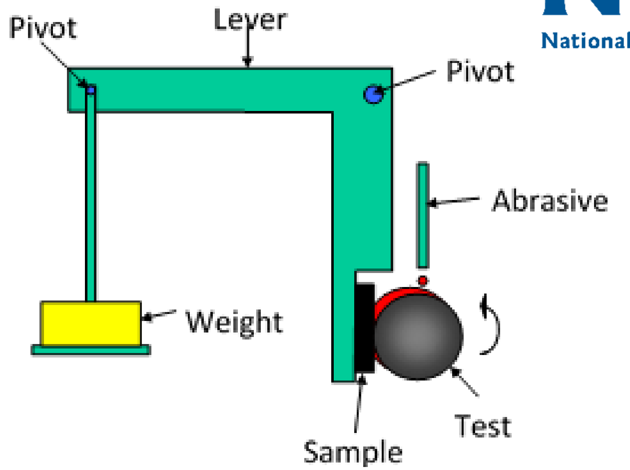
VAMAS $Si_3N_4$, $Al_20_3$, steel, ~40 labs, 2 exercises

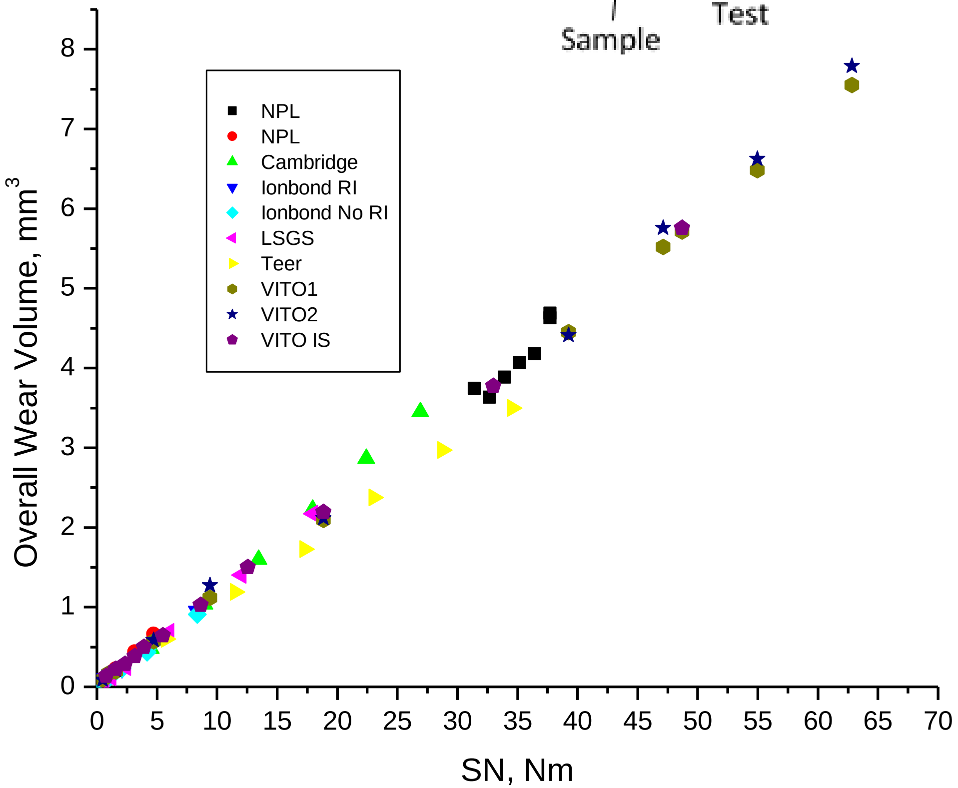


NPL pin-on-disc alumina



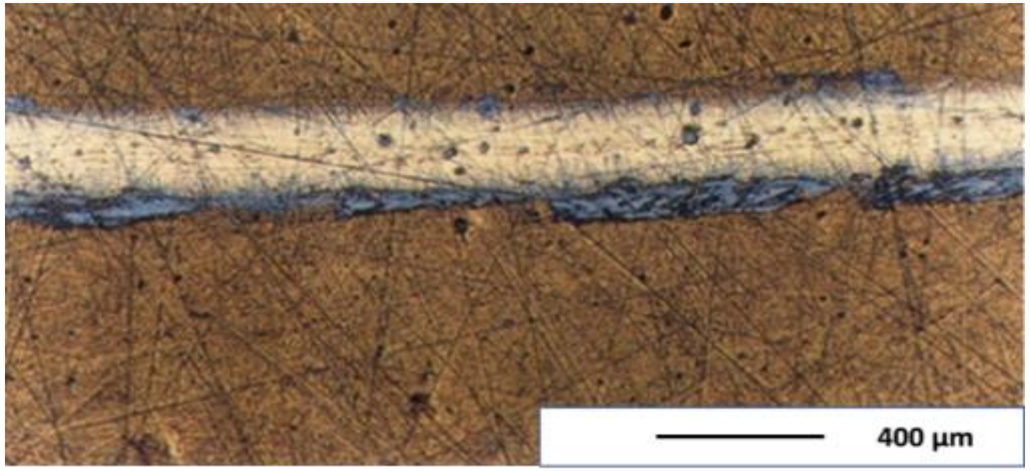



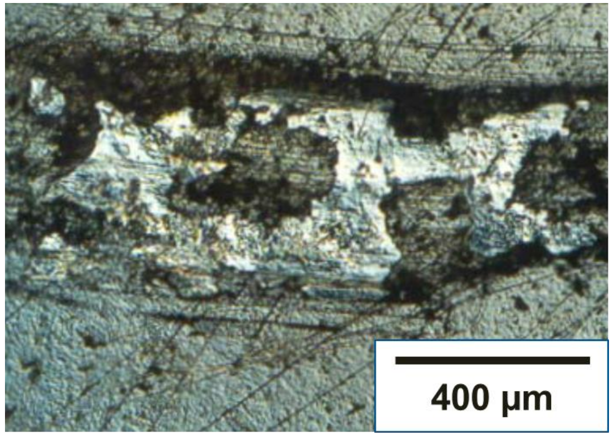

EU Crater project, Microscale abrasion 3 μm TiN

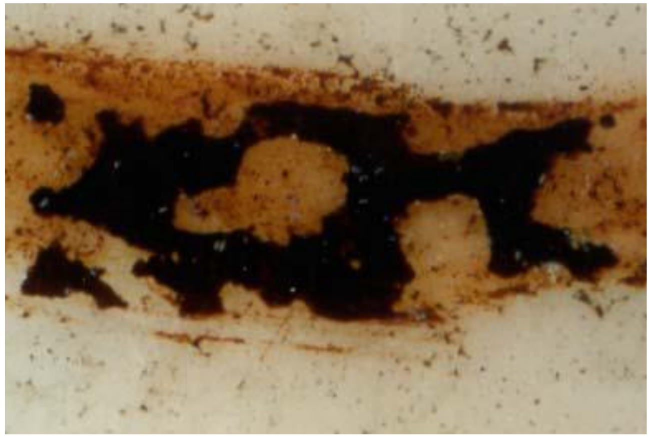
# Surface Characterisation

- Need to correlate wear and friction that occur with details of microstructure
- Allows understanding of relationship between damage mechanisms and microstructure to be built up
- Necessary before any physical modelling activity can be carried out
- Wide range of techniques available today:
  - Visual examination
  - Optical microscopy including 3D optical microscopy
  - Profilometry
  - Scanning electron microscopy with FIB and chemical analysis
  - Transmission electron microscopy
  - Surface analysis techniques




Optical micrograph of wear to TiN coating

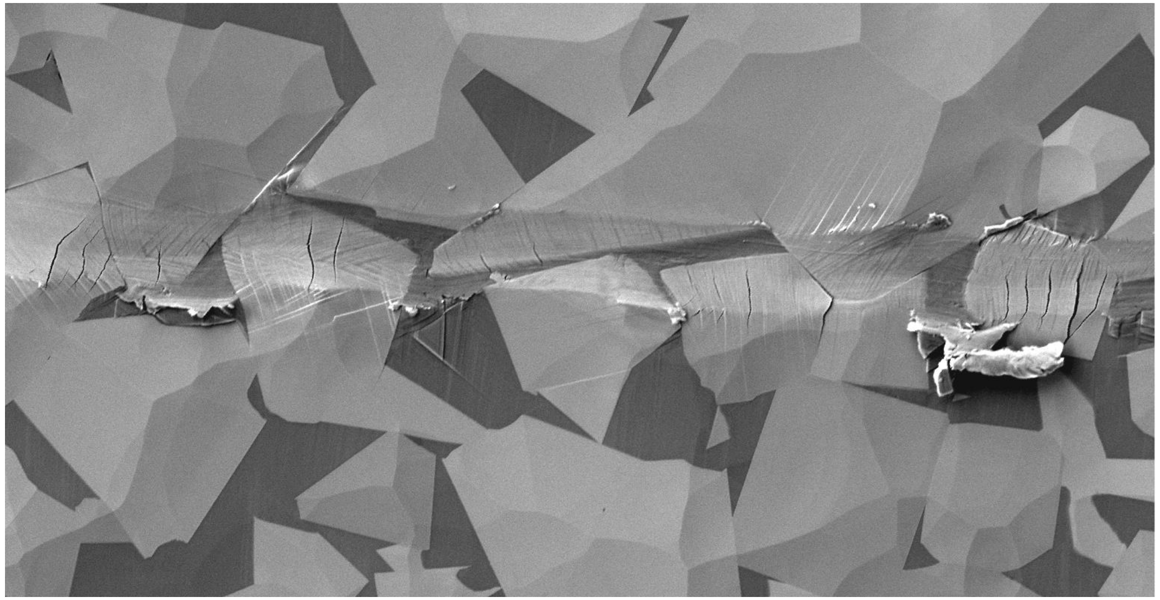


Optical micrograph of wear track with steel ball against alumina disc, left bright field image, right polarised light image

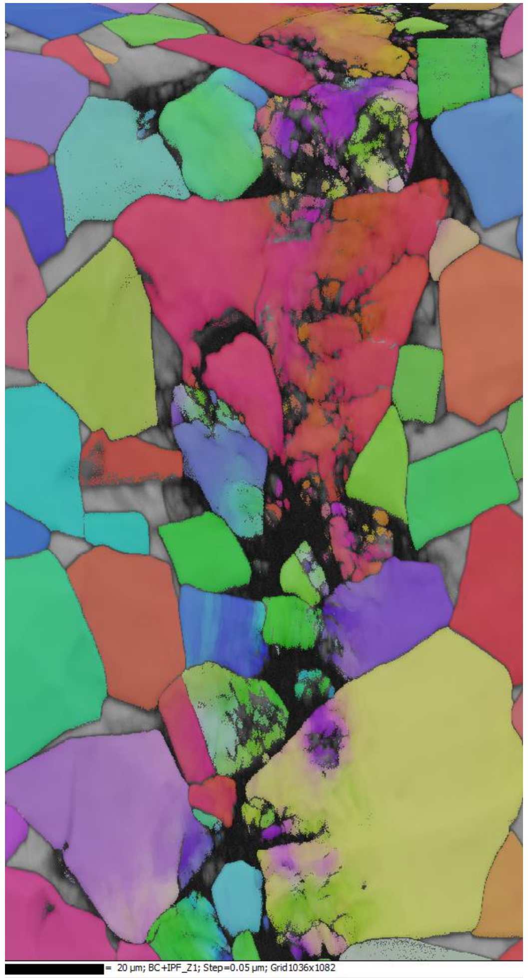
# SEM of Model Abrasion Scratch

- WC/Co tool material 80mN scratch
- SE image shows plastic deformation and cracking in WC/Co grains
- Electron Backscattered Diffraction (EBSD) shows orientation of grains and reveals damage to grains (IPF)
- Misorientation map shows damage (green) related to plastic damage in the WC grains

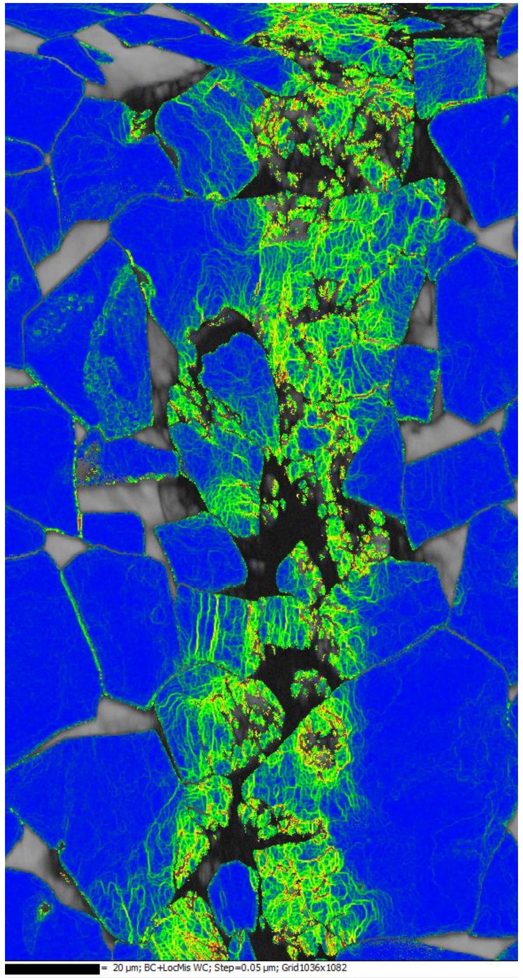


Secondary electron image

EBSD



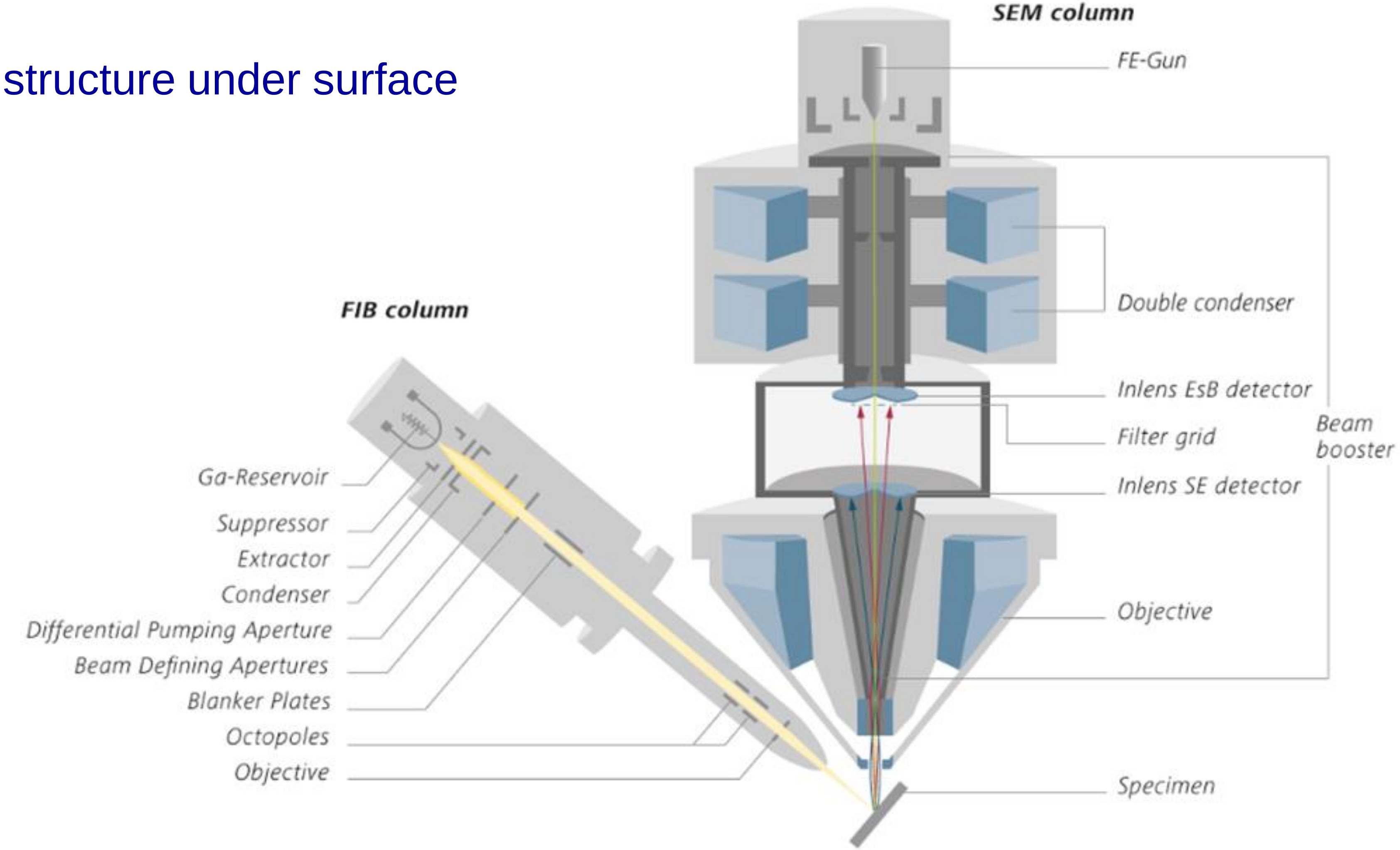

Crystallographic orientation map (inverse pole figure (IPF))




Misorientation map

# FIB-SEM

- FIB machining to reveal sub-surface structure
- Can be used to investigate way sub-surface structure of features on surface
- Can build up full 3D analysis of structure under surface



# WC/Co Model Abrasion Test

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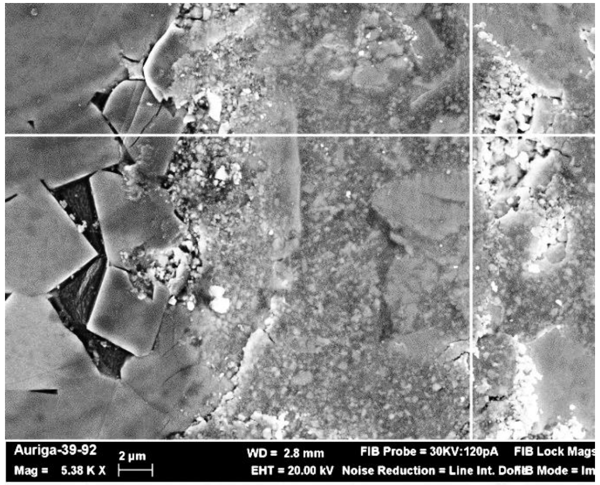
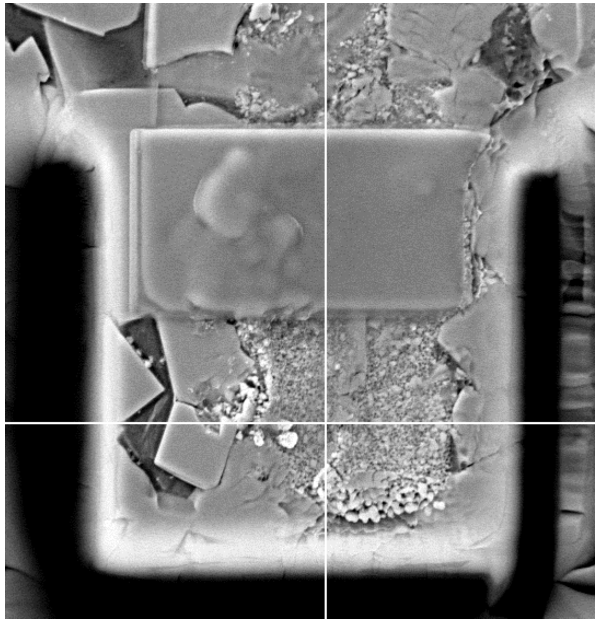
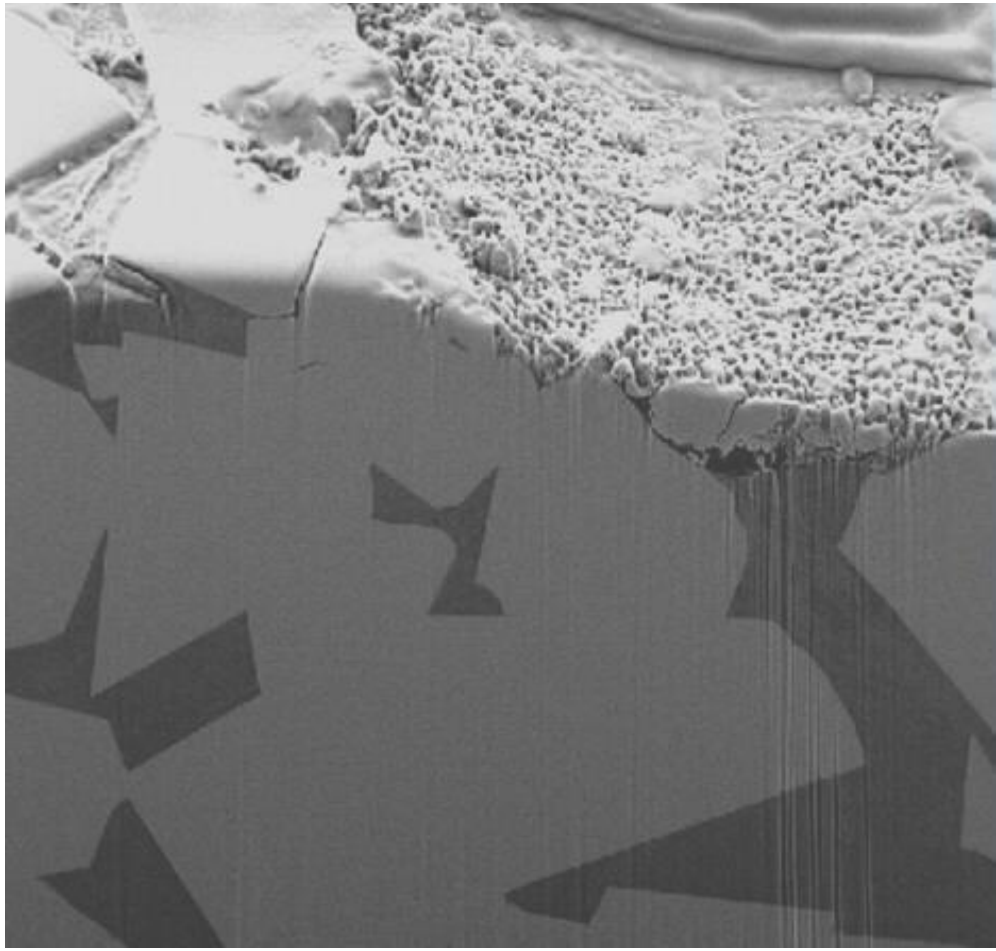
- 2000 pass scratch (same position) on WC/Co tool material sample
- Sample prepared for 2D analysis
  - Pt layer sometimes required to protect surface
  - Trenches cut around area of interest for “garbage”
- 3D analysis confirms extent of surface fragmentation and sub-surface cracking

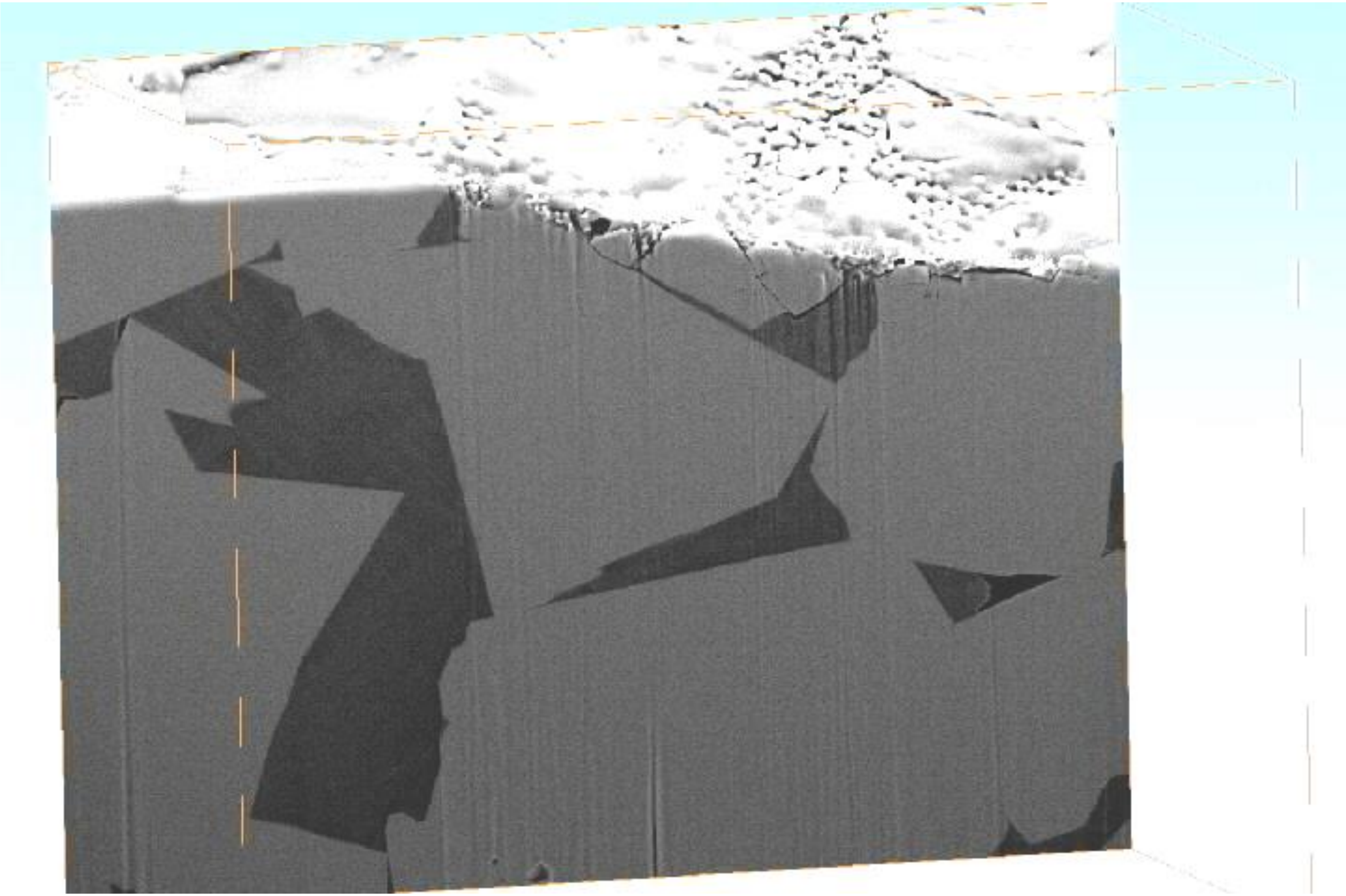




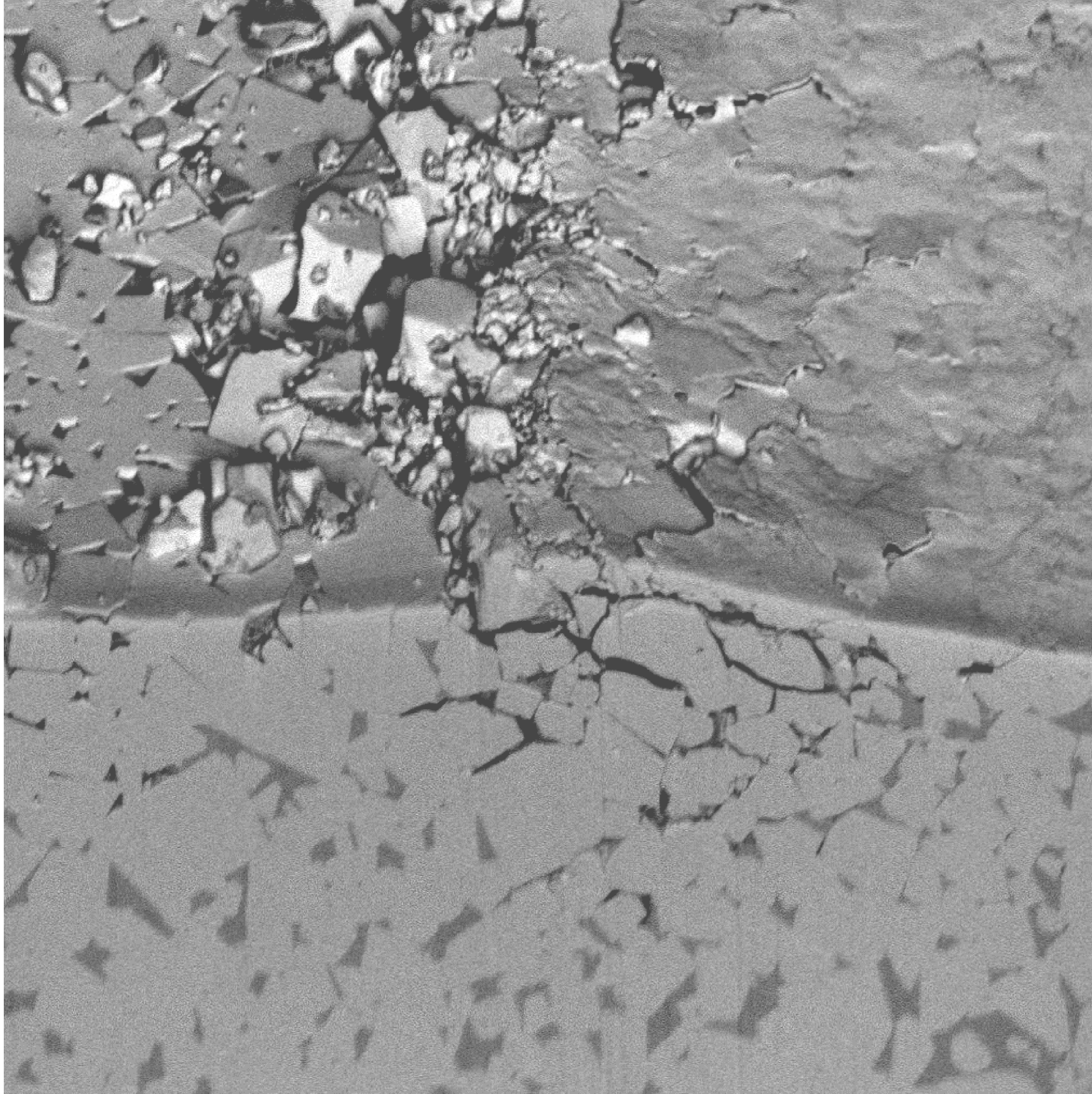
# WC/Co Model Abrasion Test

- 2000 pass scratch on WC/Co tool material
- Careful analysis can distinguish cracking (red) from other sub-surface structures
- Results can be viewed from any angle
- Connectivity of crack network is important parameter



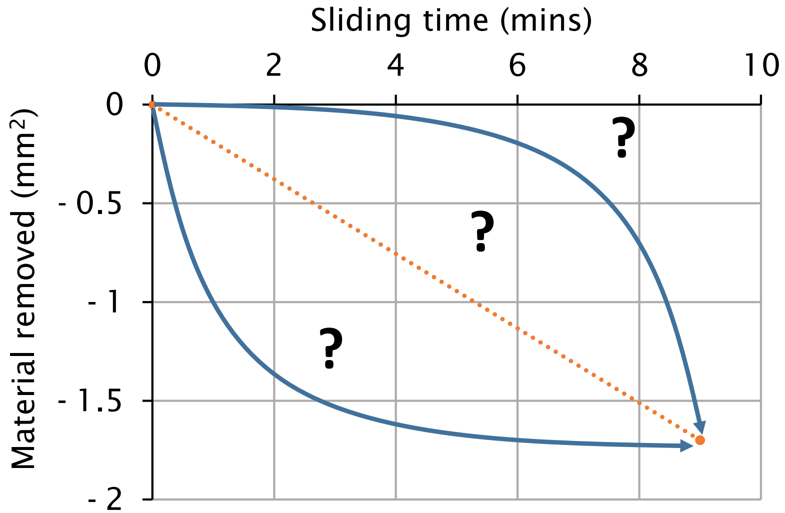
# WC/Co Model Abrasion

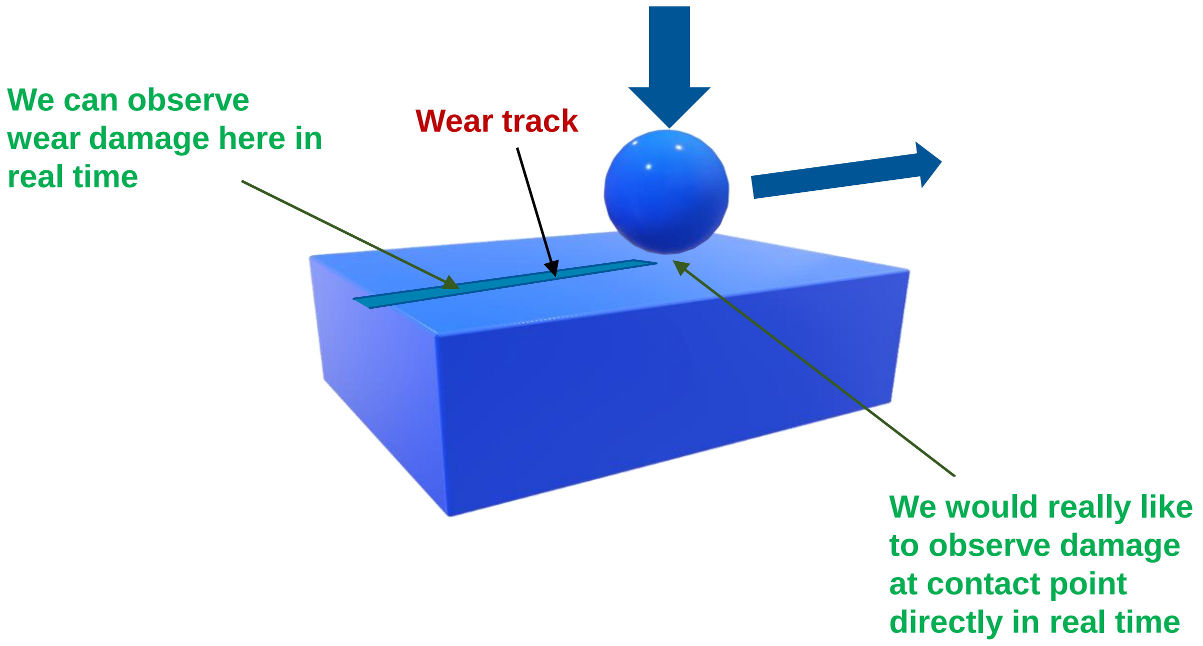
- 2nd example
- 200 N scratch load
- Scratch with compressed surface layer of material on right
- Original surface on left
- Sub-surface network of cracks
- Edge uplifted
- Loose WC grains
- Many more cracks than actually visible at surface



# Wear

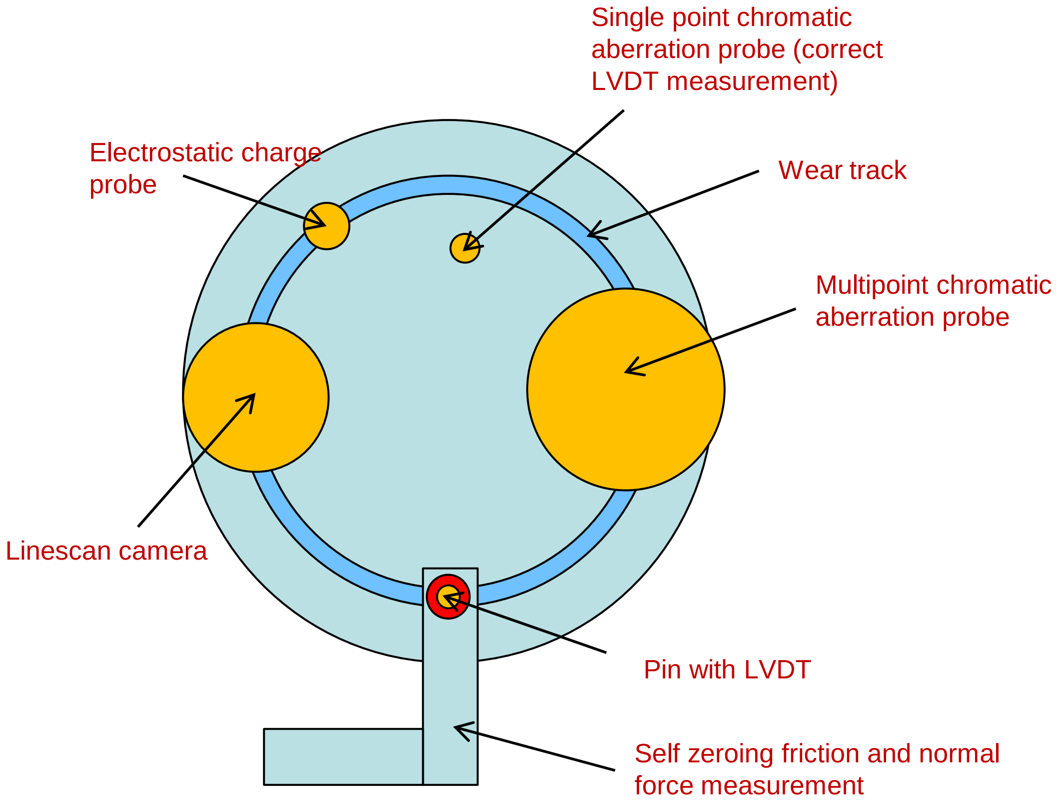
- Very complex phenomena of many types with many factors affecting what occurs
  - Difficult to measure what is occurring
  - Nearly impossible to measure what actually occurs at contacts
  - Normally evaluate damage after tests
  - For sliding wear one surface is always in contact
    - Can observe actual contact point in limited ways (eg transparent materials)
- Alternative is to measure damage in real time on the surface that moves away from contact
  - Reduce number of tests required to map tribo-contact wear mechanisms
  - Much more information gathered as test proceeds



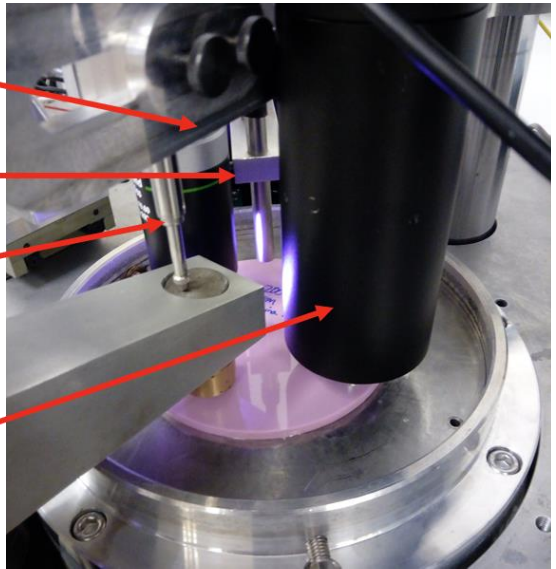



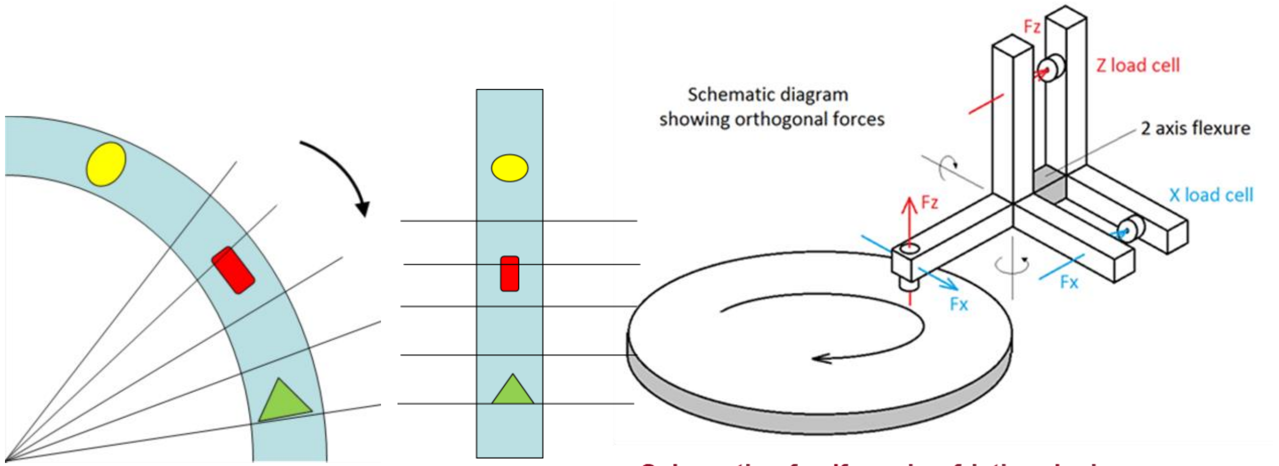
# NPL Integrated Tribometer

- Pin-on-disc system
- Loaded through lever system below machine table or actuator system
- Allows unrestricted access for multiple sensors
- Current focus on line-scan camera for visual imaging and multipoint chromatic aberration probe for real time profilometry
- Successfully used in tests with clean lubricant




- Linescan camera
- Single point chromatic aberration probe
- LVDT
- Multipoint chromatic aberration probe



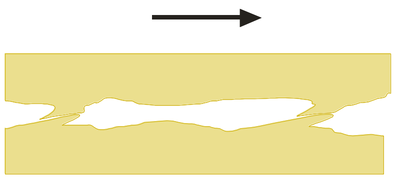



Schematic of self zeroing friction device

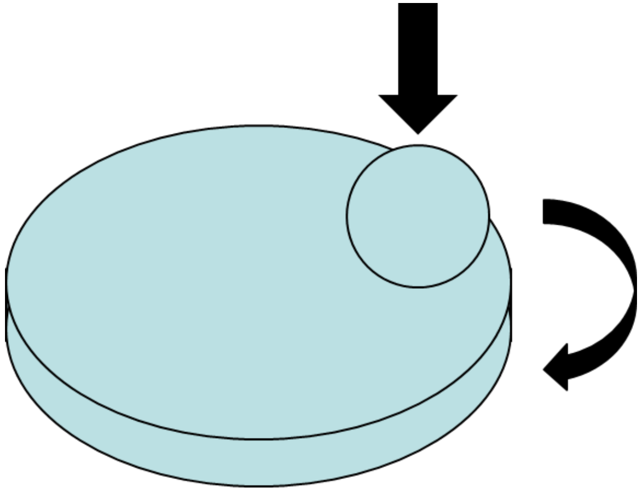
# Rotating Ball on Disc Test

- Example:
  - Steel ball vs Alumina disk
- Continuous rotation
- Allows real time examination of build-up of damage
- Parallel monitoring of friction and other parameters

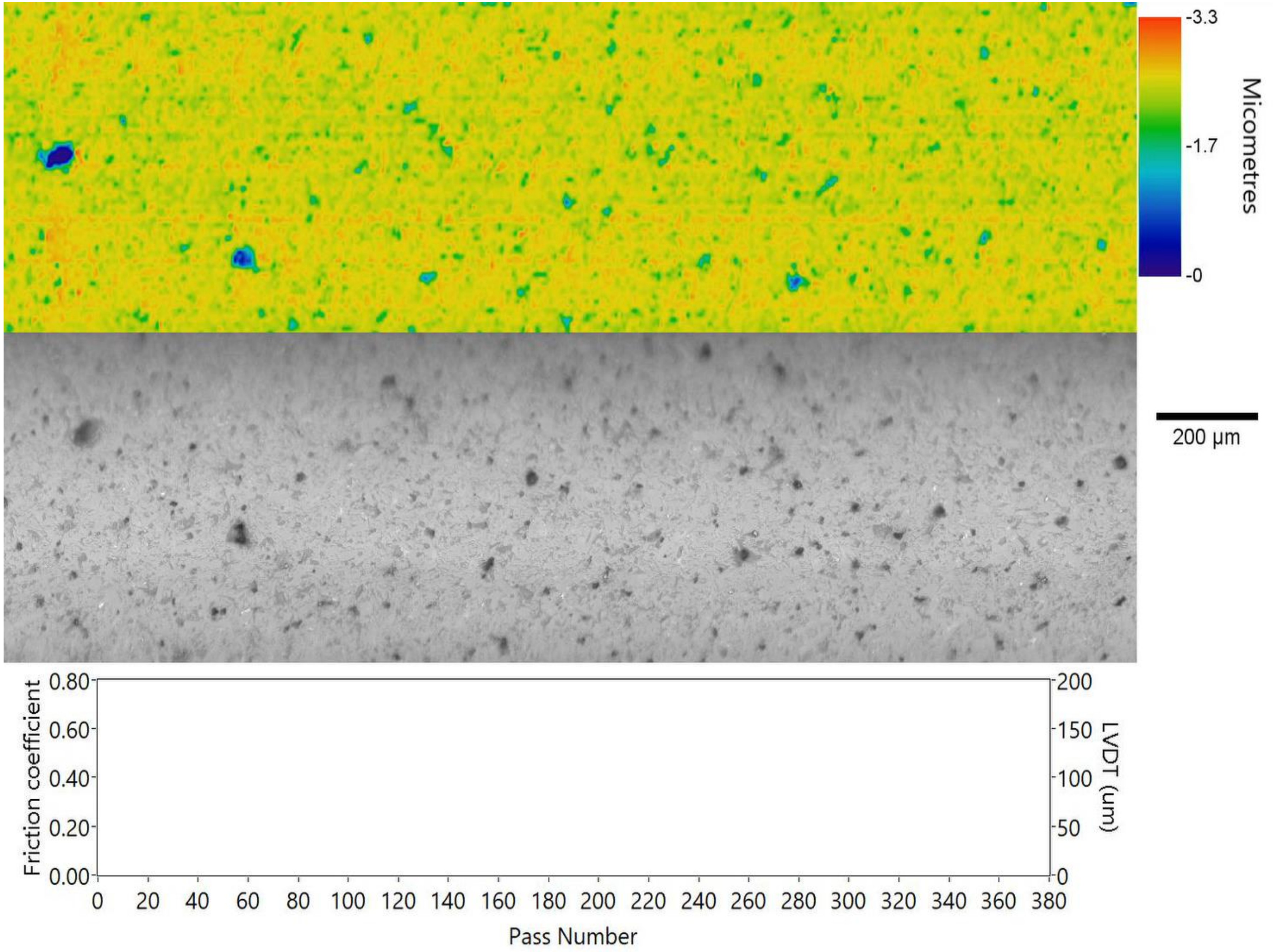
**Adhesive wear**

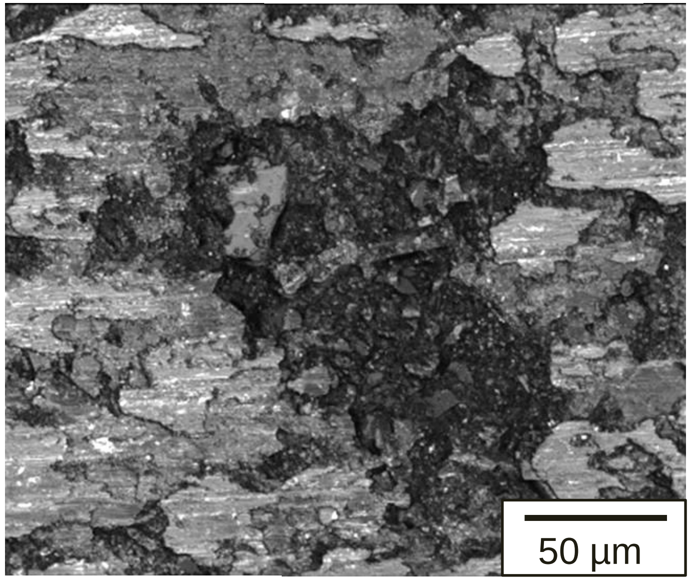


Adhesive wear from the rubbing together of relatively smooth surfaces

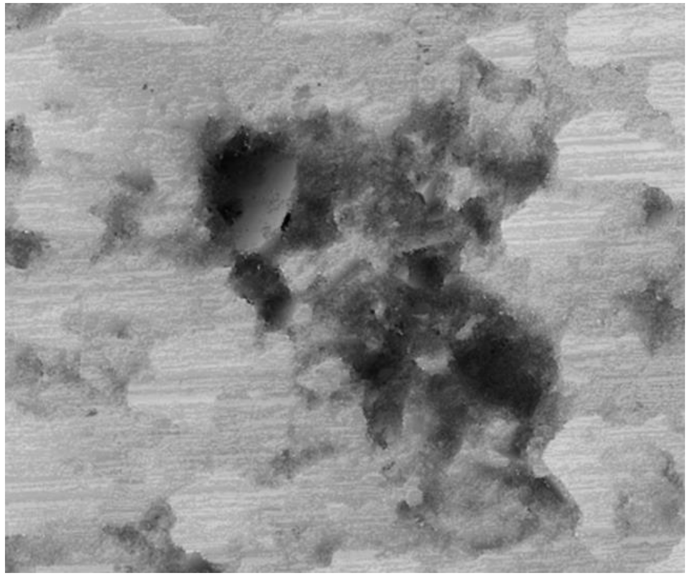


# Steel Ball against Alumina Disk




Confocal Image

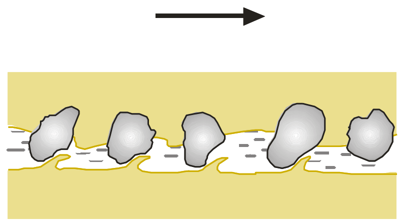


Height map

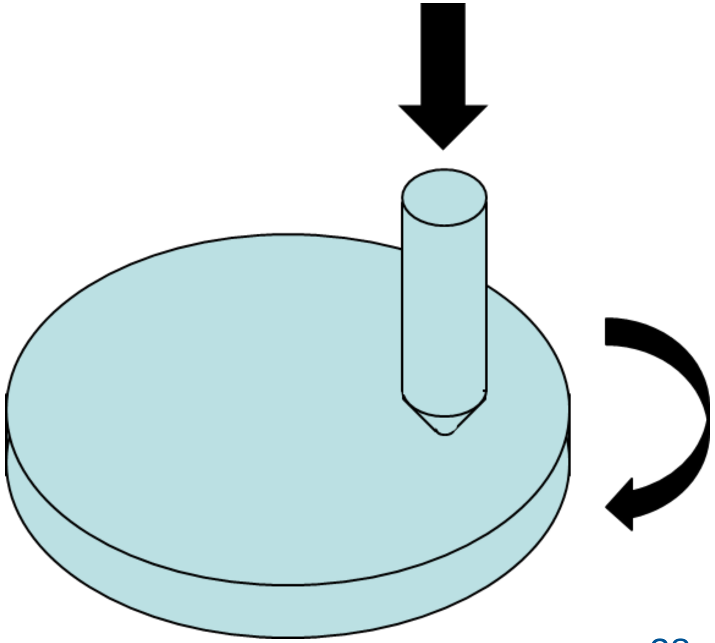
# Rotating scratch rest

- Similar to linear scratch test
- 200 µm radius diamond indenter
- Steel, alumina and TiN coating
- Continuous rotation
- Allows real time examination of build-up of damage
- Parallel monitoring of friction

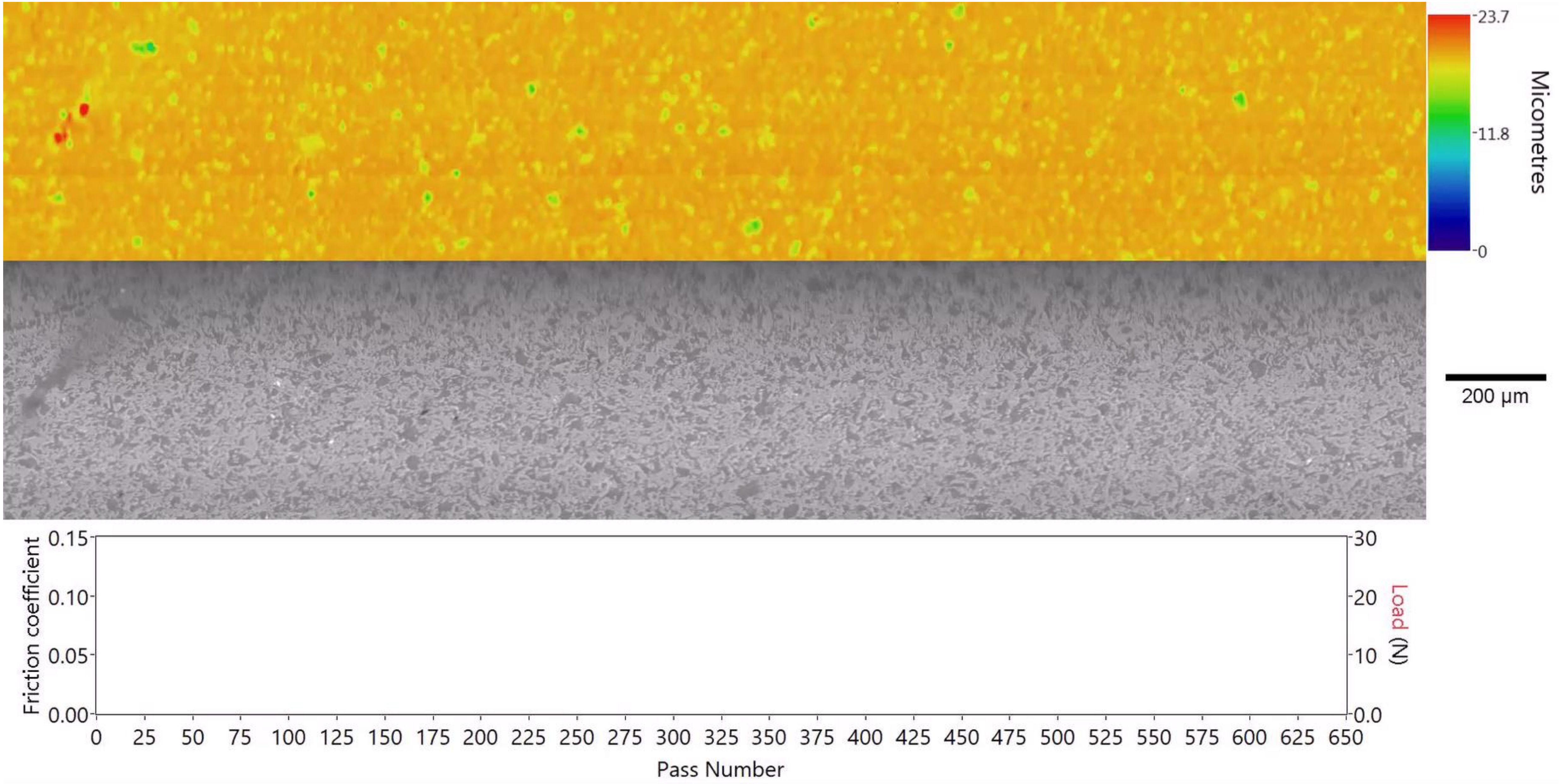
**Abrasive wear: 2 body / grooving**



Abrasive wear from hard sharp particles trapped between moving surfaces



# Indenter Against Alumina Disk

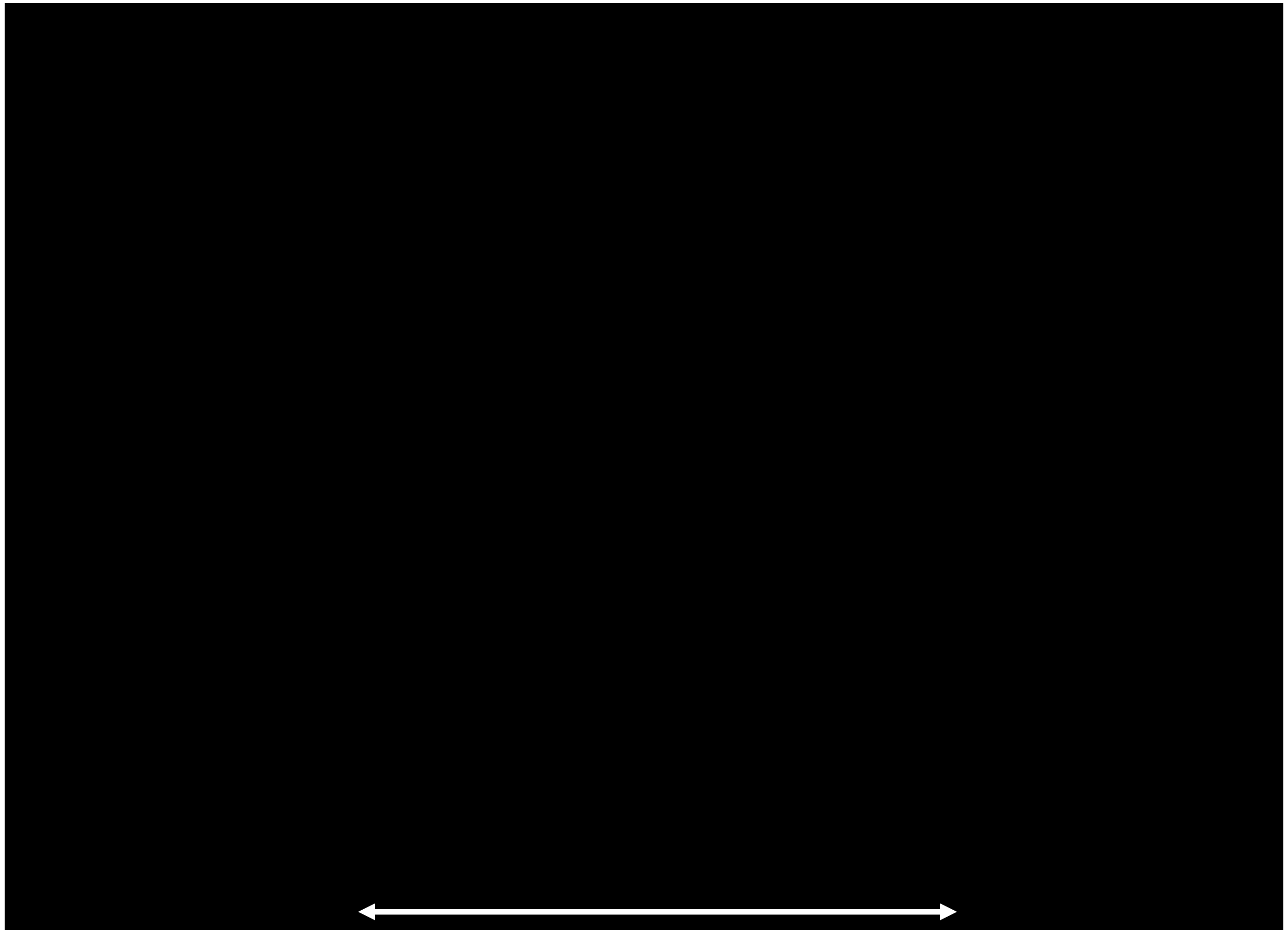


# Thermal Imaging

- Temperature of contact point is important factor in understanding sliding wear
- Little understood
- Make use of IR transparent hemispherical sapphire contact and high resolution IR camera to image hot spots at contact
- Example of experiment with alumina
- Note that contact points are very transient (order of ms duration) and move around continuously
- Temperature increase is quite high and will alter properties of materials locally

National Physical Laboratory

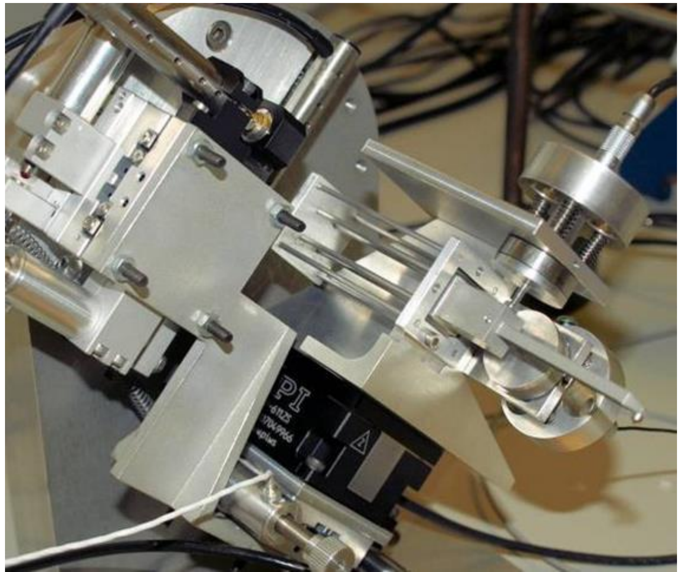
Sapphire half sphere



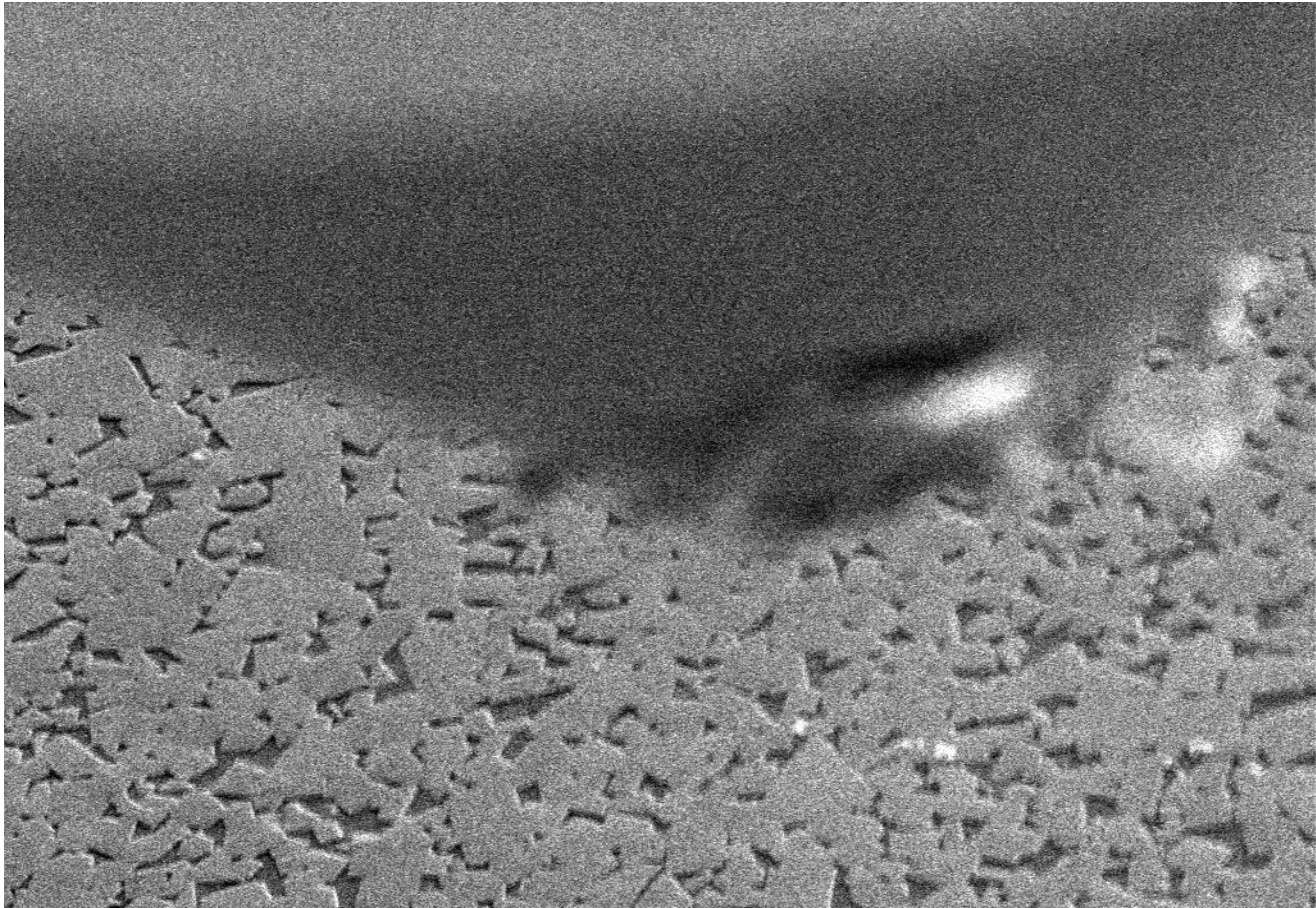
Contact Zone

# *In Situ* (SEM) Microtribology

- Test system (below) provides ability to determine damage to sample *in situ*
- Scratch in with diamond indenter
- Enables details of damage mechanisms and relationships with microstructure to be determined
- First: in situ experiment on WC/Co hardmetal
- Second: Results for VBN 480 WC AM alloy



**In situ experiment on WC/Co hardmetal**



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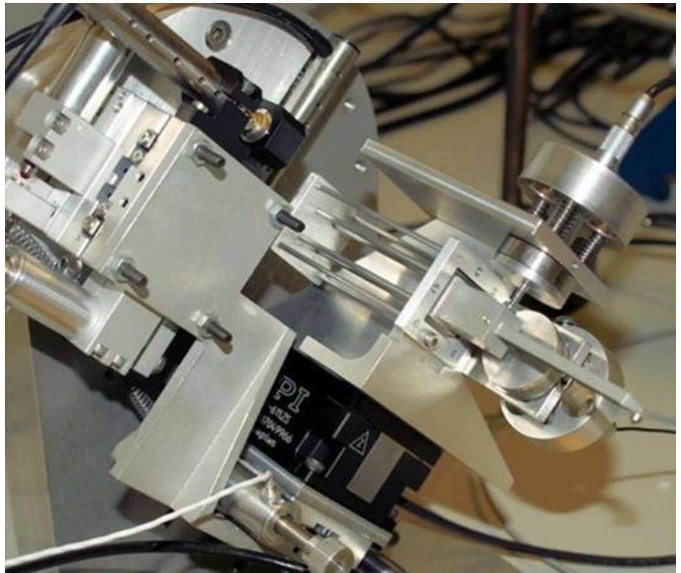
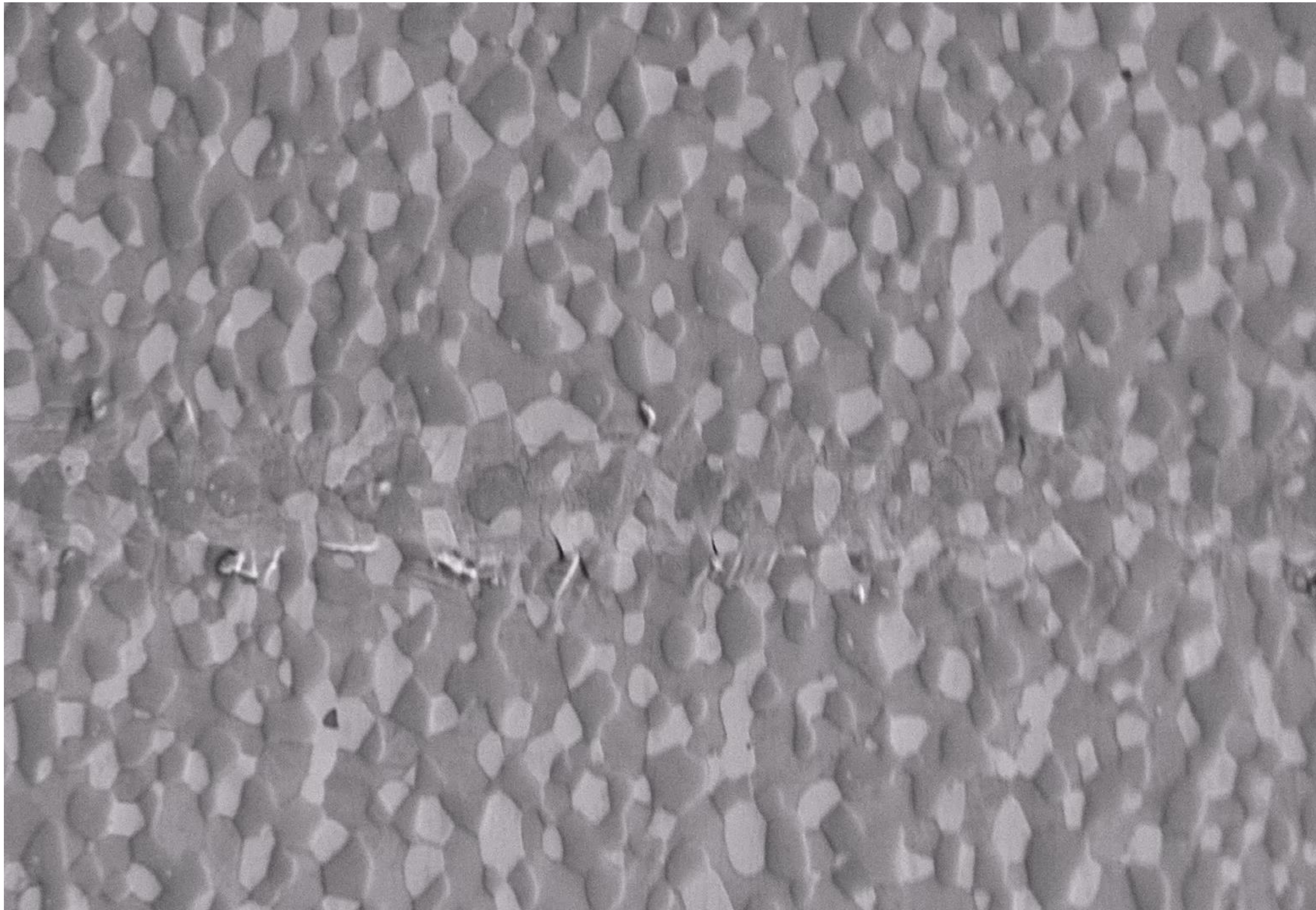


**Results for VBN 480 WC AM Alloy**



# Relocation Profilometry - Rough Surface Uncoated

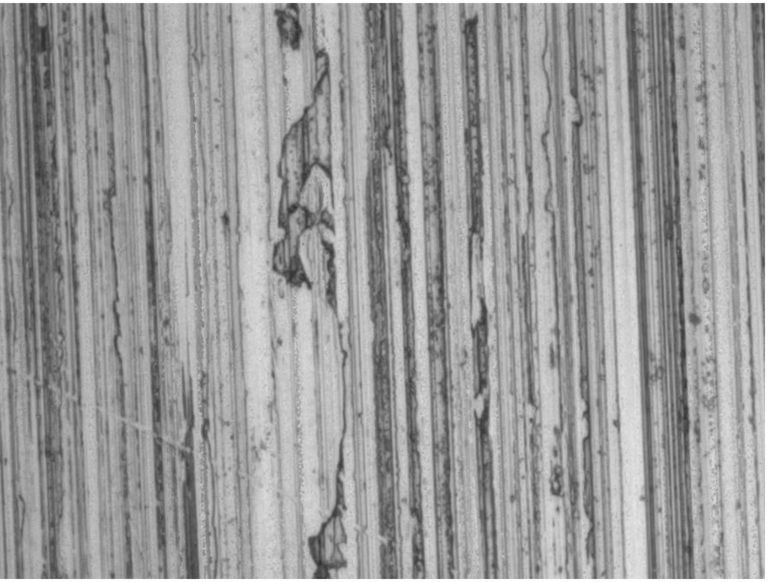
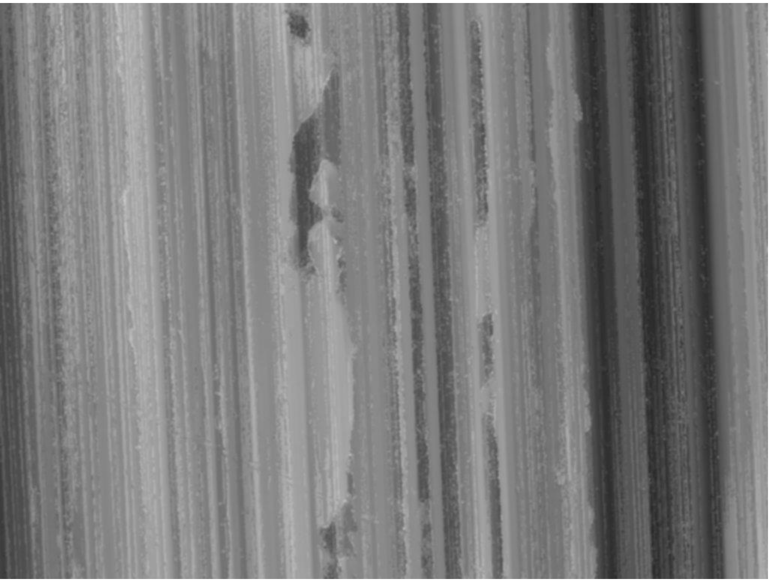


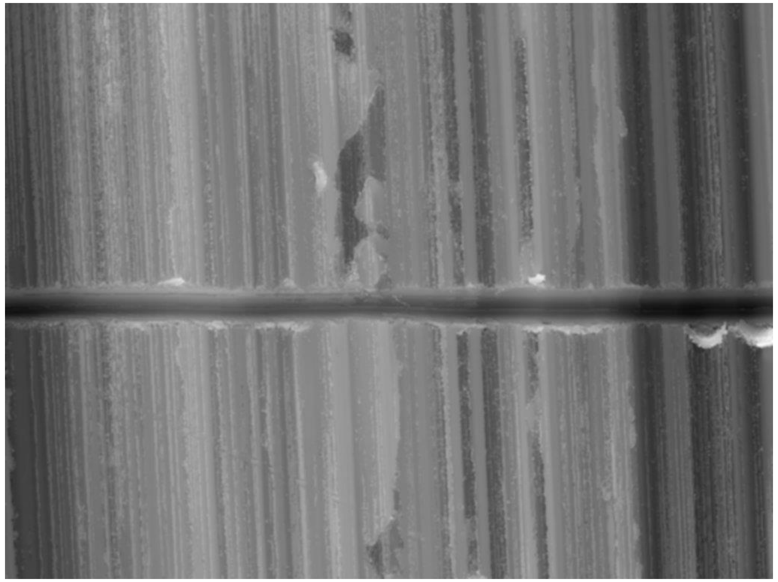
Image before

Image after

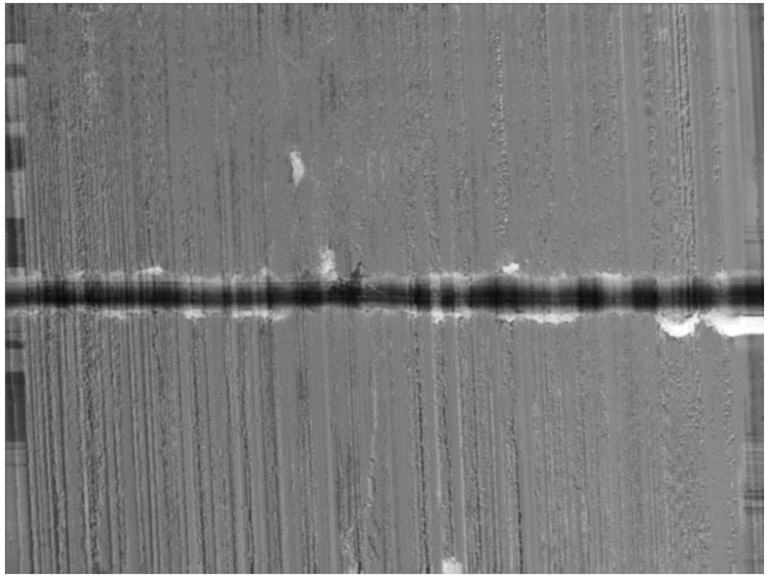
- Ground steel surface 0.1 µm Ra hardness 6 GPa
- 120 mN load, 1 µm radius diamond indenter
- Lext confocal microscope giving simultaneous image and height data
- Relocation before and after
- Subtraction of before and after height maps
- Gives accurate measure of damage even on rough surfaces



Height map before



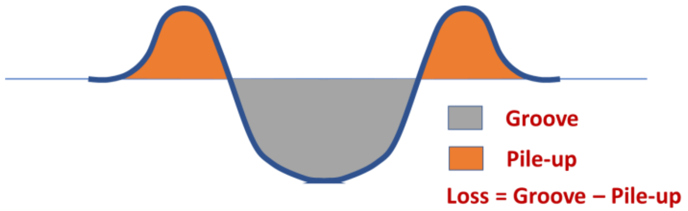
Height map after

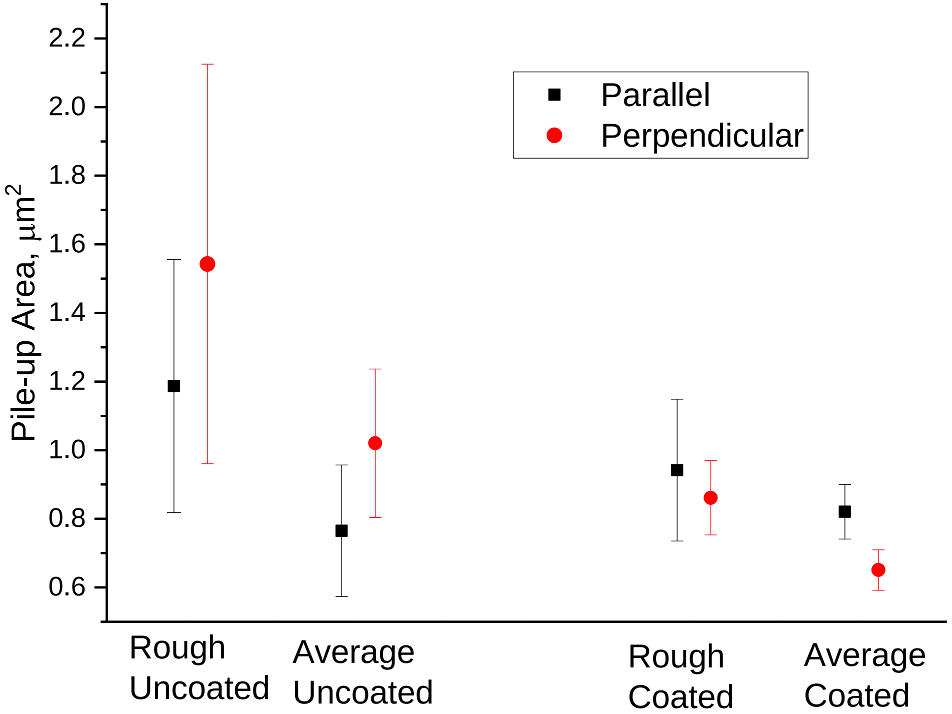


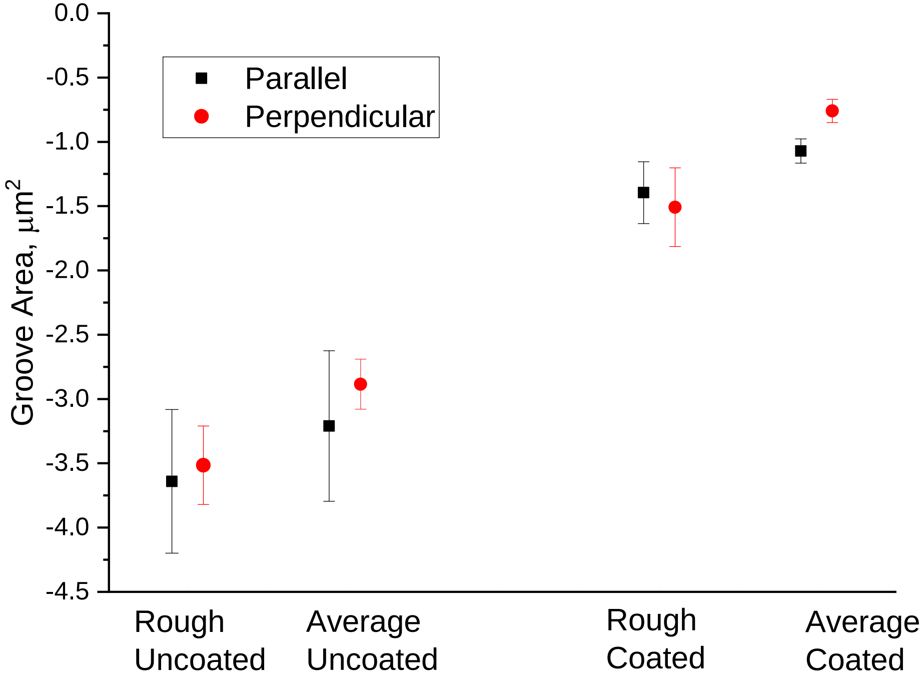
Height maps subtracted

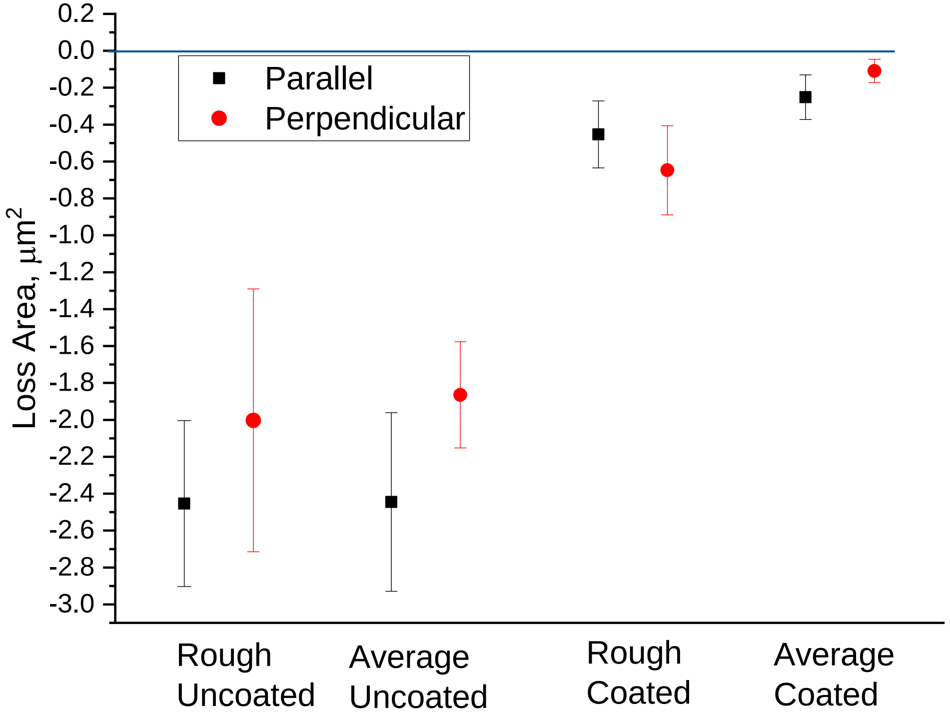
# Wear to Coated and Uncoated Samples

- Two roughness values, rough is 0.1 µm Ra, average is 0.012 µm Ra
- 120 mN load, 1 µm radius diamond indenter
- Graphs show cross sectional area defined by diagram
- Wear is ~12 times lower (volume) with coating



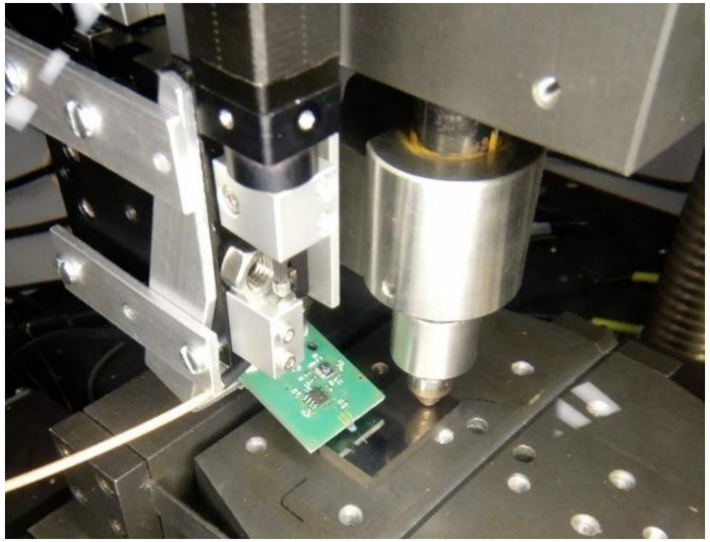



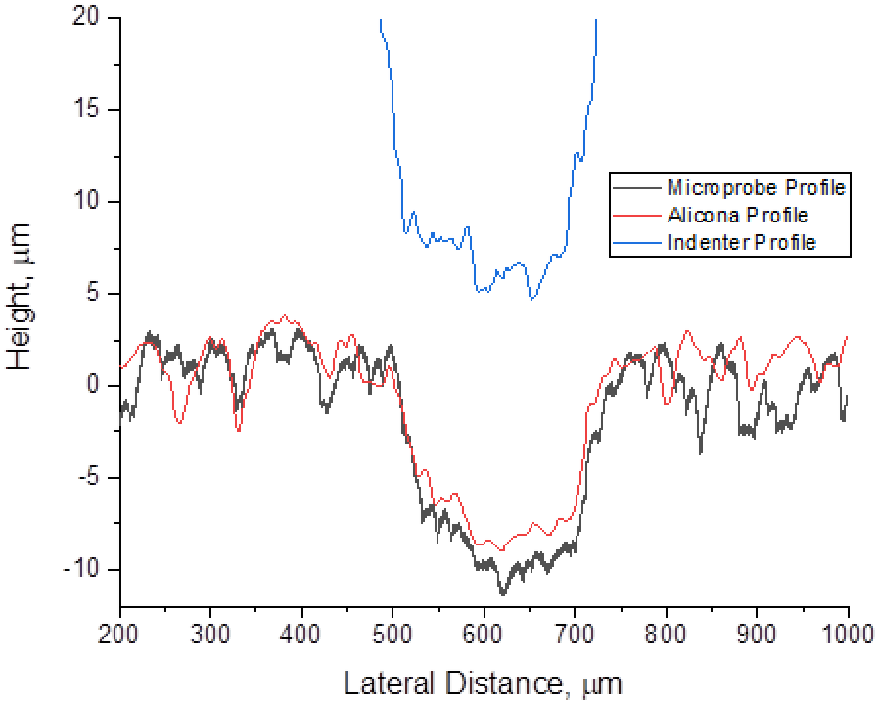



# Microprobes EMPIR project

- European project
- Us of piezoresistive contact probes into on-line measurement
- Our role (with Pheonix Tribology) is to introduce these probes into tribological testing
- Developing them for TE77 reciprocating rig, pin on disc and SEM microtribometer
- Demonstrated successfully with static in-situ experiments so far
- Need to move onto live measurements soon



Test setup




Results

# Summary

- Reviewed the importance of wear and friction
- Reviewed how measurement can contribute to help understand wear and friction with goal of reducing wear and controlling friction
- Demonstrated capability for in-situ testing to give information that enables real time control of test
    - Vastly increased understanding of processes that occur and relationship of mechanisms to microstructure
    - Relocation profilometry can measure wear to rough surfaces accurately

***Future***

- Positioning for digitalised tribological testing – validated assured data and understanding of tribological phenomena
- Online and offline *in situ* friction and wear measurements to inform AI and advanced digital control
    - Adjust test parameters in real-time to achieve control of wear mechanisms
    - Terminate test during wear transition for advanced ex-situ analysis
- Tribological issues in transition to EVs including lubrication

Note:

Collaboration always welcome on use of NPL facilities, contact Mark.Gee@npl.co.uk or Timothy.Kamps@npl.co.uk

# Thank you for your time

Department for
Business, Energy
& Industrial Strategy

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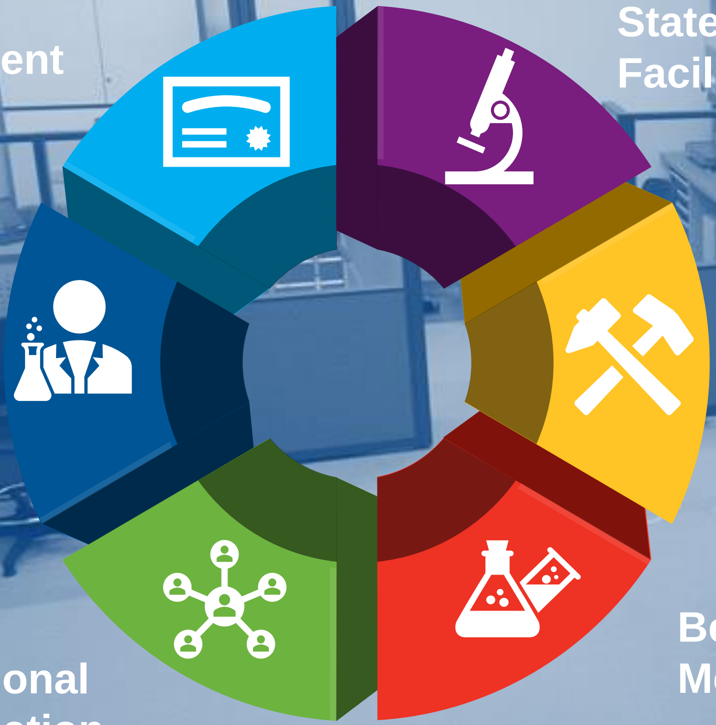
The National Physical Laboratory is operated by NPL Management Ltd, a wholly-owned company of the Department for Business, Energy and Industrial Strategy (BEIS).

# Q&A Session

**Dr Stefanos Giannis** – Science Lead
Advanced Engineering Materials

**Professor Mark Gee** – NPL Fellow in Surface Engineering and Tribology

**Dr Timothy Kamps** – Higher Research Scientist
Advanced Engineering Materials

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